EVALUATION OF A MATERIAL HUB AS A CIRCULAR WASTE MANAGEMENT STRATEGY

A CASE IN HAARLEM MUNICIPALITY

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Abstract

Dutch municipalities face the waste management problem of assets which are reaching their end of life cycle. This is why, they investigate ways to effectively tackle this issue, by simultaneously complying with the goal imposed by the Dutch government about 100% circular construction sector by 2050 [43]. As a preparatory step in the transition towards Circular Economy (CE) in the Netherlands by 2050 and the forecasted changing regulations in waste management, a material hub is deemed as a solution to the waste management concern on the level of municipalities. For this reason, the Dutch public authorities are searching a unified framework to evaluate the impact of the material hub as a circular waste management strategy. The main objective of this study is to create a decision-making tool from the municipalities' perspective to explore the circumstances under which the material hub can contribute to circularity objectives in waste management domain, given the increased cost incurred, and assess the future feasibility of the material hub.

In order to achieve the above-stated objective, this research, first, introduces the concepts of circular waste management practices in the Netherlands and the material hubs based on the academic evidence and exploratory discussions with relevant professionals. Moreover, it entails literature review of recent publications relevant to waste management models and specifically Reverse Logistics (RL) models. Second, this study describes the conceptual framework of the defined problem:

- by categorising all the construction and demolition waste (CDW) into fifteen material clusters that reflect sufficiently the various waste streams in municipalities
- by translating circularity in this context
- by configuring a RL supply chain which is universally applicable for the fifteen material clusters.

Third, the methodology used to provide a solution to the postulated problem is formulated together with simplifications for transforming the actual problem into optimization model. Fourth, the real-life problem is simulated in a mathematical model, which is then tested in the municipality of Haarlem. Fifth, the data for this case, which is either gathered or generated and inserted as model inputs, is summarised. In data generation, various scenarios of supply-demand ratio of returned materials are used. Sixth, the model results are evaluated in order to determine whether the material hub can lead to economical and circular objectives.

Finally, conclusions are drawn about circumstances under which the material hub is financially viable investment for the Haarlem municipality. The cost effectiveness of the material hub is determined by two criteria. The first one is that investment in the material hub as waste management practice could evoke cost savings for the municipality in comparison with the current strategy. This is achieved by giving a new purpose to returned materials and avoiding buying all materials needed in new construction projects. The second financial criterion is the required storage capacity of the material hub. The outputs of the model for different scenarios lead to the conclusion that these two financial criteria can be fulfilled when the supply is higher than demand for returned materials. More specifically, it is concluded that in scenarios with supply-demand ratio of 2:1 and 3:1, cost savings can reach 2.5-3.6% and 10.8-12% respectively compared to the current situation. In parallel, circular objectives are realised within the aforementioned scenarios. It is identified that the optimal objective values (minimum cost, maximum circularity and minimum CO_2 emissions) are not obtained simultaneously in one scenario. Subsequently, the optimal solution is determined depending on the focus of the decision-makers in the municipality. Furthermore, it should be commented that even though financial and circular goals are accomplished under the specific circumstances, the cost savings are deemed relatively low considering the initial effort and time of building a material hub. Another implication from the model results is that only limited quantity of returned materials is actually stored at the material hub. This is in contradiction with the intended basic function of the material hub as storage facility.

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Introduction

While the construction sector is contributing in the enhancement of economy, it is also considered as one of the largest consumers of raw materials (50%) and energy (40%) [16, 42]. As the demand for housing due to increasing population is growing more and more (from 7 billion to 10 billion world citizens by 2050), the extraction for raw materials has an uprising tendency (4% annual increase) [27, 43]. However, the natural resources are not inexhaustible and reusing resources is becoming more and more incumbent in the last decades [28]. Moreover, it can be stated that the construction sector generates approximately 46% of the total amount of waste in Europe every year [17]. The Ministry of Infrastructure and Environment expects an increase in construction and demolition waste (CDW) generation up to 32 megatonnes (Mt) by 2021 [8]. Even though the environmental impact of CDW is low in relevance with other waste streams, its high volume leads to environmental concerns regarding its logistics and land occupation [17]. According to Fu et al., 10.000 tons of CDW occupy 0.067 hectares of land [16]. For the aforementioned reason, the CDW management is gathering more and more the attention of the experts, especially in Europe [6].

The European Commission recognised the necessity of establishing policies for efficient waste management across the European countries and proposed Circular Economy (CE) targets for facing the challenges of CDW [17]. In a relevant study, it was illustrated that efficient resource management can decrease the resource rate by 17% and increase GDP by 1.6% by 2050 worldwide in comparison with the current practices [12]. In this context, the waste management prevention and the conversion from linear to circular waste management systems are recommended, incentivising the full exploitation of waste by increasing the reuse and recycling rate of returned materials [7].

1.1. Background

1.1.1. Reverse Logistics concept

The notion of CE is approaching the concept of closed-loop supply chains (CLSC), since the materials reuse and recycling can lead to closing the materials loop [18]. The CLSC management was introduced to enable the decision-makers to strategically design how materials can be recovered efficiently. CLSC entails a combination of Forward (FL) and Reverse Logistics (RL) materials flow [44]. FL is the procedure in which the materials move "from points of origin towards points of consumption" [25]. The main discrepancy between RL and the FL is the aim of recovering materials in the highest economic value as reasonably possible, meaning that only the materials with no retainable value can be regarded as waste and can be disposed in the landfills [25]. Subsequently, according to Hosseini, Rameezdeen, Chileshe & Lehmann, RL process can be regarded as the return of materials from the "consumption point to the point of origin" or to "secondary consumption points", such as markets outside the construction sector [26]. The focal point of RL is management of materials recovery once they can no longer be used, aiming for financial benefits by reuse, remanufacturing or recycling [2]. Particularly, the RL procedure can be deemed as the process of materials collection, inspection, categorisation and repair/ remanufacturing/ recycling/ reuse/ landfilling according to the decision taken based on their quality [51].

1.1.2. Challenges of Reverse Logistics

While the RL is emerging more and more in the construction field and has potentials for circular waste management, a few steps have been taken to facilitate its implementation due to fundamental barriers [22]. In the past, structures were constructed for durability with non-reversible adhesives resulting in law possibilities for deconstruction [43]. Deficit of guidelines in the current building codes and technical specifications about the complex dismantling procedure may demotivate the RL initiation. There is also high level of uncertainty involved in the RL projects related to lack of well-trained manpower and education, limited experience and high labor costs because of the manual sorting of materials [21, 25, 31, 43, 59]. Other challenges are the high cost of machinery, the uncertain performance of materials after the RL process and space constraints for the RL activities. Besides, the long lifespan of structures with changing ownership can hinder keeping track of the material quality and project characteristics. In virtue of the new emerging technology, newly manufactured materials exist in the market at lower prices than the recovered materials, making the reclaimed materials market uncompetitive [28]. For instance, the average price for an upcycled lamp is €180, while the primary product costs on average €95 [41]. Because of the aforementioned lack of awareness about the RL procedure, designers and architects still have a perception that the use of recovered materials entails a lot of performance uncertainties, so it was noticed that they do not prefer these materials in the construction of new buildings [26].

1.1.3. Opportunities of Reverse Logistics

On the other hand, there is no doubt about the economic potentials of RL, since material circulation can lead to more than $ 700 billion cost savings, achieving economic growth up to 4% for the next 10 years [6, 15]. Specifically, it is mentioned that revenues from reselling the recovered items or avoiding the cost of manufacturing virgin materials and the landfill taxes (including logistics) make the RL projects more cost-effective [17, 25, 26]. According to qualitative studies, the initial cost of dismantling activities exceeds (around 21%) the costs of conventional demolition procedure. However, if the whole life cycle costs are considered, the dismantling has better economic benefits (37% less cost) in comparison with the traditional demolition after reselling/reusing the reclaimed materials [25, 28]. Besides, RL as circular CDW management can induce tremendous environmental benefits, since according to relevant research, CO_2 emissions could fall by 83% in 2050 comparing to the CO_2 levels in 2012 [13]. Because of the economic and environmental returns, RL is gathering not only the academia's attention but also the professionals' attention, which perceive the RL of products as a business opportunity and embed the RL activities in their decision-making during the business models formulation [2].

1.1.4. Leading role of public sector

The actors in the construction sector are sceptical about the transition from conventional to circular waste management due to the high financial risk involved. However, the public sector should play a leading role in the shift to RL as circular waste management. Through imposing new regulations or giving financial incentives, implementation of CE practices can be scaled up on regional, national and even international level [6]. Besides, governmental parties can develop strategies to introduce the circular waste management by investing in small scale pilot projects to explore its economic viability before applying this procedure in larger scale projects. Subsequently, experience can be acquired and concerns about the financial feasibility can be overcome to stipulate the private companies to embed the circular waste management in their practices [6].

1.1.5. The Netherlands

The focus of this research is RL implemented in the Dutch environment as circular waste management strategy. The Dutch construction sector is accountable for 50% of raw materials consumption and 35% of CO_2 emissions, whereas the CDW is affiliated with around 40% (around 65 million tonnes per year) of total waste (around 461 million tonnes per year) in Europe [27, 39]. The Netherlands imports 68% of raw materials needed from abroad, highlighting the dependency of Dutch economy on other countries due to the material price volatility and material supply [43]. The Dutch Government has set the ambitious goal of fully embracing CE in the construction sector in the Netherlands by 2050, meaning that materials will be used or reused in an efficient way with minimum loss of value and harmful emissions into the environment [43]. Nowadays, approximately 95% of CDW is recovered, among which 85% of CDW is mostly recycled to road foundation and aggregates for concrete (Figure 1.2) [42]. 4% (1 million tonnes) of CDW and 16% (4 million tonnes) of CDW are landfilled and incinerated to generate energy respectively [27].

Nevertheless, the main CE principles for the "technical materials" are the following. The technical cycle of materials can continue by following the shortest possible route to insert again to the life cycle, by having as many iterations of life cycles as possible, by preserving the value of the materials as high as possible, by minimizing waste generation and energy consumption and by assuring that the structures can be dismantled in a safe and easy manner (Figure 1.1) [7].

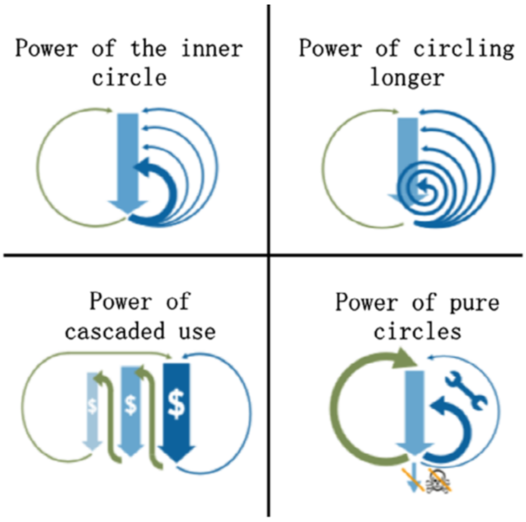


Figure 1.1: Four sources of value creation for circularity [15]

So, according to CE principles, recycling is regarded as a downgrading process as materials are used in a lower value purpose [6]. Consequently, despite the fact that recycling CDW is happening at a high rate, it can be claimed that the Dutch construction section cannot be perceived as 100% circular [42].

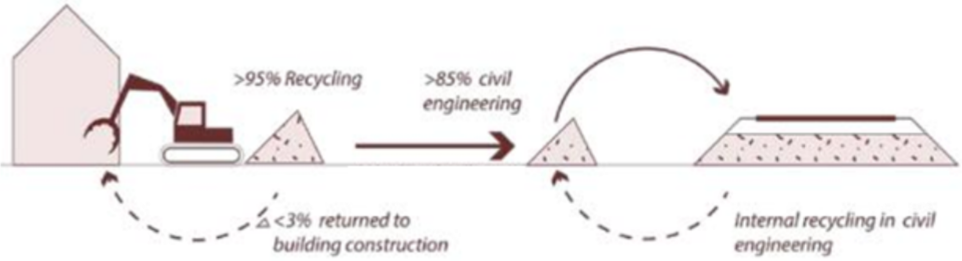


Figure 1.2: Construction and Demolition Waste in the Netherlands [42]

1.2. Problem description

Following a brief literature review and an exploratory discussion with experts in the municipality of Haarlem, the following problem statement is postulated.

The Dutch construction sector should comply with the CE paradigm by 2050. In order to accelerate the transition towards circularity, governmental bodies can overcome the doubts about the financial feasibility of circular waste management by initiating small scale pilot projects before applying them in larger scale projects [6]. An important line of action should be taken to move forward the 100% circular construction field: the conversion of traditional waste management to RL stimulating the circularity of returned materials. However, the construction sector continues the conventional waste management because of no substantial changes in the project budget [17]. So, there is a necessity for the public administration sector to find instruments to reinforce the decision-making of how to implement the CE strategies, such as RL, in an economically viable way [17].

The municipality of Haarlem, together with its private partners, encourages circular entrepreneurship and is interested in circular business to establish itself as a circular city. According to an introductory discussion with professionals in the municipality of Haarlem, a huge spectrum of infrastructure assets and public buildings are approaching the end of their life cycle and the problem of public CDW management is attracting more and more their attention [57]. Among their plans related to CE paradigm, projects reaching their maturity level are deconstructed and a database is developed in which the quantity of materials derived from deconstructed projects in the municipality is registered, creating the potential for reusing them in future projects. While there is information about location and time that the returned materials are released, the quality of returned materials is not recorded after the deconstruction of projects. On the other hand, new projects are planned to be constructed in this topographical region within a certain time horizon and quantity of materials required in the new projects can be estimated [57].

The objective of this database is to close the material loop and facilitate RL procedures in the municipality, matching the supply of returned materials with the demand for materials in new projects in terms of quantity, quality and time within a specific time horizon. The current RL practice implemented in Haarlem is that after the deconstruction of projects, the returned materials are dispersed in various warehouses within the municipality and are transferred to new projects without a concrete plan for material flow, possibly effectuating limited revenues and ignoring the quality aspect of returned materials along with orienting them in lower value purposes. Planning is required for RL strategy followed by the municipality to accomplish circular and cost-effective material flow. To the question posed to the municipality and its partners, regarding a way to optimise the material flow plan between supply and demand of materials, the answer was investing in a material hub, in which returned materials are collected, inspected, categorised based on their quality and accordingly distributed in the market. Concerns raised about this proposition by the municipality experts regarding the economic viability and the contribution to the circularity of materials [57].

Li et al. [35] stated that the collection centers of returned materials are required for a profitable RL network. Further exploration regarding the financial feasibility of the material hub is necessitated by the municipality. The investment of building a material hub involves the consideration of its environment and the interrelations, entailing the future demand points of the returned materials as potential sources of revenues. Decisions should be made in order to determine the facilities involved in RL supply chain. However, the RL network design cannot be standardised because of the uncertainties involved in RL and mainly the varied nature of processed materials [29, 36]. So, the municipality is dealing with the issue of designing a RL environment incorporating the material hub which can be generally applicable for the diverse waste streams and reflect the reality in a sufficient level [57].

John, Sridharan and Kumar pinpointed that the separation, categorisation and storing of returned materials in the collection centers aim in controlling the quantity and quality of returned materials before the distribution to the market in the desired time, quantity and quality [29]. Those procedures have potentials in terms of circularity, in the sense that the returned materials might be oriented only towards upgrading purposes once relevant demand is recorded. Adhering to the CE ambitions and the goal of moving towards circular waste management, the municipality questions whether investing in a material hub can enhance the circularity of materials [57].

In view of the novel scenario of building material hubs, knowledge about their operation is lacking. Variation of the quantity and quality of materials between demolished and new projects in different time periods leads to divergence of capacity requirements of the hub within the time horizon considered. So, the capacity of the hub as an intermediary node between demolished projects and new projects is in question [57]. Consequently, determining the requirements of the material hub within the time horizon is essential for the municipality before proceeding to the material hub construction.

To sum up, the municipality of Haarlem has committed to engage CE principles in their current RL practices. Investment in a material hub within municipality is proposed as a circular waste management strategy. In the hub, the returned materials, following deconstruction of projects, are concentrated and categorised before being transferred to the potential clients. The municipality before realising this investment, investigates whether this proposition is worthwhile for the optimal circularity of materials between demolition projects and new projects given the increased cost occurred. Two problems should be faced by the municipality before delving into the scenario of this investment. Initially, the aforementioned proposition entails the process of materials coming from both infrastructure projects and buildings owned by the municipality. Hence, the professionals in the municipality are dealing with the difficulty of assuming a generally applicable RL supply chain including a material hub to simulate the material flow during the time horizon defined. Secondly, the dynamics in supply and demand rate of materials within the time horizon raise the question of requirements of the material hub.

1.3. Scientific and practical relevance

1.3.1. Scientific relevance

The environmental and financial potentials of material hubs were highlighted in the literature and certain case studies (Section 2.2.1), but in practice some material hubs in various EU cities failed for various reasons. The contribution of material hubs in economic and environmental terms as a CDW practice cannot be assessed easily in projects because of the heterogeneity of returned materials (in range, volume, quality and timing) and the difficulty to standardise the parties involved in treatment of returned materials. Other possible reasons are that the revenue potentials were wrongly conceived and the associated business plans were not viable [56]. Moreover, the diversified pattern of supply and demand of materials within a time horizon and high uncertainty level involved in material streams prediction could not facilitate the decision-making about factors in the collection centers, such as their number, operation, location and capacity requirements [35, 45].

Derived from the previous section, the impact of material hubs as a waste management strategy in financial and circular terms is missing, considering a supply-demand fluctuation of returned materials for a time horizon. To deal with the identified problem, a decision-making tool regarding material hubs is required considering conflicting factors for making a trade-off analysis between them. In Operation Research (OR) literature, similar multi-criteria decision-making problems were tackled [52]. This research constitutes an integration of RL model concepts which are divided into the following categories: environmental objectives, uncertainties in quality categorisation of returned materials, uncertainties in quantity of returned materials and supply chain network design (analysed in Section 2.3). This study contributes to the academic research as follows.

In comparison with other models in which the objective of circularity was either not embedded or separately optimised, this research will entail a multi-dimensional model embracing circular aspects. In particular, the main objectives of this study will be to maximise circularity and minimise CO_2 emissions given certain range of cost incurred for financially viable investment of material hubs within a defined time horizon. Another difference of this research with the models reviewed is that it is intended to measure circularity in a standardised way for various construction waste streams in the Dutch environment and not limited to one material. Lastly, in relevant literature, the uncertainty in various models was approached by conducting sensitivity analysis, generating scenarios based on historical data, formulating robust and fuzzy optimization models, but in the current study, the uncertainty in supply-demand quantities will be approached by generating random scenarios of diversified supply-demand distributions within the time horizon.

1.3.2. Practical relevance

As a preparatory step in the transition towards CE in the Netherlands by 2050 and the forecasted changing regulations in waste management, this study will create a unified framework for the municipalities to evaluate the material hubs as a circular waste management technique. This analysis will define a relationship between the cost and circular dimensions in the material hubs under varying supply-demand dynamics. Subsequently, the municipalities will be able to explore the extent that the material hubs can contribute to circular objectives in waste management domain, given the additional cost incurred, and eventually proceed in construction of material hubs or not.

1.4. Research objective and research question

1.4.1. Research objective

From the problem statement, the following goals of the proposed research are defined. To tackle the first problem, the objective of the proposed research is to design a RL network including a material hub which can be applied to returned materials deriving from both infrastructure assets and buildings in Dutch municipalities. Following the assumption about the RL supply chain, the second sub-problem is addressed, which is determining the requirements of the material hub in function of material flow between returned materials and materials in new projects within the given topographical boundaries and the time horizon. Once those requirements are figured, the main objective is investigated which is to explore whether the material hub constitutes an economically viable waste management strategy and simultaneously contributes to circular objectives.

1.4.2. Research question

Derived from the problem context and research objectives, the main research question is established as follows:

"Under which conditions is it profitable for the municipalities in the Netherlands to invest in building a material hub as a waste management strategy, while achieving circular objectives?"

The aforementioned research question will be answered by initially providing answers to the following sub-questions.

1. What are the key concepts in the identified problem?
    (a) What clusters of materials can be used to represent the diverse construction and demolition waste streams in the municipality?
    (b) Which actors can participate in a Reverse Logistics environment for diverse construction and demolition waste streams in the municipality?
    (c) How circularity can be measured for diverse construction and demolition waste streams in the municipality?
2. What is the proper model to provide a solution in the identified problem?
3. Which is the outcome after applying the model in the municipality of Haarlem?
    (a) Which are the circular objectives for cost-effective material flow of construction and demolition waste in the municipality?
    (b) What are the requirements of the material hub for diverse construction and demolition waste streams in the municipality?
    (c) Which are the most important factors of influencing costs in the model?

1.4.3. Research outline

In the second section, the circular waste management practices in the Netherlands are briefly investigated and knowledge is acquired about the operations in a material hub based on the academic evidence and exploratory discussions with relevant professionals. Additional literature review of recent publications relevant to RL network models is embodied in this section.

The third section entails simplifications for the defined real-life problem based on the literature review findings and interviews. The first sub-question is answered by categorising all the CDW into material clusters to reflect sufficiently the various waste streams in municipality, by determining circularity and by configuring a RL supply chain which can be universally applicable for the material clusters.

The methodology followed in this study is elaborated in fourth chapter. In particular, the approximations for transforming the actual problem into optimization model are entailed and the solution steps to provide an answer to the main research question are catalogued. In the fifth chapter, the real-life problem is simulated in a model, answering the second sub-question.

The sixth section contains data for case characteristics in the municipality of Haarlem, which are either gathered or generated. In the seventh chapter, the data from Haarlem case are inserted in the model, inducing to results. Scenario analysis with variations in the model inputs is conducted which corresponds to different relations between the cost and circular objectives of the material flow, answering the third sub-research question and eventually the main research question.

The last chapter provides the scientific and practical contribution of the research, concluding comments providing an answer to the main research question and future research recommendations.

2

Literature Review

In this chapter, based on the academic evidence and exploratory discussions with relevant professionals, the current state towards a circular environment in the Netherlands will be briefly investigated. Knowledge will be acquired about the material hubs as a waste management technique in the transition to circular construction sector. The remaining of this chapter entails literature review of recent publications relevant with waste management models and specifically Reverse Logistics (RL) models focusing on the following concepts: environmental objectives, uncertainties in quality categorisation of returned materials, uncertainties in quantity of returned materials and supply chain network design.

2.1. Transition to circular construction sector in the Netherlands

2.1.1. Circular construction sector

Initially, definition of linear and circular concept in the construction sector are given. Linear procedure is known as a take-make-dispose process of materials, assuming unlimited natural resources, meaning that once the primary resources are extracted will be processed, used as construction materials and landfilled in their end of life cycle [6]. On the other hand, the Circular Economy (CE) paradigm refers to decoupling economic growth from the raw materials consumption and entails principles in which materials are used as long as possible in closed-loop supply chains (CLSC) (if possible) [6, 37]. In this context the raw materials are (re) used in an efficient way, the value of materials remains as high as possible, so the dependency on raw materials and the environmental damage can be decreased [3, 50].

2.1.2. Guiding factors in the transition to circular construction sector in the Netherlands

In 1979, the "Ladder van Landsik", known as "Waste hierarchy by Landsik" was submitted with the aim of prioritizing the Construction and Demolition Waste (CDW) management policies and is deemed as the base of CE in materials supply chains [23]. The "Waste hierarchy" is the following: reduce (prevent waste and use products efficiently), reuse (transfer directly or after cleaning/ minor repairs the returned materials to customers), recycle (process, separate and reuse of returned materials in such a way that their purpose varies from the original materials), recover (incinerate waste and produce energy), landfill (in case of no further usability of materials) [2, 39]. The initial legislation about waste management was detected in a directive in the Environmental Management Act (Wet Milieubeheer- Wm) in 1994, which was adjusted multiple times the following years and constituted the basis for the future National Waste Plan (LAP) introduced in 2003 which entailed the first Waste Framework Directive. LAP 2 was established in 2009, while the regulation document about waste prevention plan , "From Waste to Resource (Van Afval Naar Grondstof, VANG)" was published in 2014 [8]. In the aforementioned regulation frameworks, the conceptual framework was established for the transition from linear to circular waste management, whereas several non-legislative instruments/initiatives like "Green Deals" followed, published (from 2011 and onwards) to give more incentives about CE in the construction sector [8, 42]. Particularly, the Association for Waste and Cleaning Management (Vereniging voor Afval en Reiningingsmanagement-NVRD) signed the "More and Better recycling" agreement (Meer en Betere Recycling onterdekend) in 2015 to improve the recycling level of the waste materials [39]. The goals set in the Paris Agreement in 2015 about minimising the greenhouse gas emissions had an evident relation with CE targets [5]. In parallel, research studies highlighted the potentials of CE in the Dutch environment in cost savings, producing 7.3 billion euros per year and creating 54.000 new jobs up to 2023. It was also estimated that the Netherlands could become less dependent on importing natural resources and minimising CO_2 emissions [19]. This was the moment that more concrete plans and policies were introduced in the Netherlands and the CE paradigm was escalated in the national agenda priorities [50].

The Dutch government developed a program in 2016 called "A Circular Economy in the Netherlands by 2050" as the base for the steps to be taken for the transition. Briefly, those goals focused on 50% decrease in the primary raw materials by 2030 and efficient (re) use of raw materials by 2050, aiming to reduce the environmental degradation. In parallel, design of new materials in a way for being reused in later stages of their life cycle was stipulated, minimising loss of their value [43]. In 2017, "The third National Waste Management Plan" (Landelijk Afvalbeheerplan-LAP3) was introduced as an instrument within this Government-wide program which establishes a hierarchy in decisions about waste management based on "Waste hierarchy by Landsik" [39]. Besides, in the legislation framework about the CDW management, increasing rate of taxes on landfilling and prohibition of waste burning were detected [8].

Based on this Government-wide program, the National Raw Materials Agreement was signed in 2017 to meet the raising demand for products in the future. This agreement was signed by 180 parties in which concrete plans for the efficient use of raw materials and reuse/recycle of waste in the sector of biomass, food, plastics, manufacturing, construction and consumer products was triggered in the Dutch economy [19].

Those actions in the Netherlands were the guiding factors for the government to develop the Transition Agenda for the period 2018-2050 for the Circular Building Economy. This time horizon was divided into the following three periods [54].

- 2018-2021: the starting point of implementing CE principles
- 2021-2030: 50% of the final goals will be achieved, meaning that the 50% of materials in infrastructure and buildings and raw materials will be reused, leading to less CO_2 emissions
- 2030-2050: the final goal will be accomplished, meaning that all materials in infrastructure and buildings and raw materials can be reused, eliminating the CO_2 emissions

2.1.3. Current state in the transition to circular construction sector in the Netherlands

Currently, the Netherlands is positioned in the first phase of Transition Agenda in which various meters were taken to move towards CE in the construction sector. Indicatively, certain instruments steering circular CDW management are mentioned. Circular products and services are required in public procurement (EMVI-Most Economically Advantageous Tender in 2014) in which the tenders are assessed based on their sustainable impact. Incentives in regulations about designing circular products and services are generated, experiments and R&D studies are stimulated, awareness and knowledge about benefits of CE are established and a common language to assess circularity is investigated [54]. Besides, the regulatory framework with landfilling/ incineration taxes and waste management plan set in 2015 strives also for more circular CDW waste management[8].

Circular innovations were detected, such as the development of environmental certificates like BREEAM-NL which assesses the sustainability of new, existing and demolished buildings to create a common language for CE [4]. Work sessions were organised to explore potentials of "urban mining" or integrating CE principles into the current CDW strategies [9]. Furthermore, another innovation is that all the construction materials will be accompanied by a digital material passport-Madaster by 2020. Madaster functions as an archiving and registration of materials in buildings to acquire insight in structure characteristics and the availability, quantity, quality of materials throughout the lifetime of buildings so they can be reused [6, 54]. Besides, Madaster can facilitate the management (maintenance and renovation) of buildings and the estimation of real estate value of objects based on the documented value of materials [61].

An inventory to picture circularity in the Dutch economy was carried out by the Environmental Assessment Agency (Planning Planbureau voor de Leefomgeving-PBL) [60], illustrating that CE was embedded in the Dutch economy with 85.000 circular innovations in various fields with various environmental and social benefits. Those innovations were mapped according to R-ladder with circular activities based on CE system developed by Mac Arthur Foundation: refuse, reduce, repair, recycle and recover [15, 54]. The activities of reuse, recycle and recover are defined in the same way in both the "Waste hierarchy by Landsik" and the R-ladder. The difference is detected in the activities of refuse and repair. The purpose of the first activity is to use products more intensively, while the purpose of the second stands for extending the lifespan of products by either repairing them or reusing some parts of the products (remanufacture) in such a way that returned products have similar characteristics with the original products [2, 60].

From the research, it became evident that around 300 innovative projects in building sector focus mainly on recycling techniques, while innovations for product reuse, repair, reduce, refuse are not often recorded [60]. According to the Dutch Ministry of Infrastructure and the Environment (Rijkswaterstaat), the Netherlands achieves 95% of CDW recycling mostly in ground and road construction, but only 3% of CDW upgrading [43].

2.1.4. Requirements for the transition to circular construction sector in the Netherlands

From the previous section, it can be concluded that the lower ranked R-ladder activities are more frequently observed in the Dutch context. Moving towards the Transition Agenda goals can be effectuated by focusing more on highly ranked R-ladder strategies, such as reuse and repair rather than recycling [60]. The priority in R-ladder strategies can be used as the tool for determining how the value of materials can be preserved in the life cycle [46]. Adjustments in the legislation are proposed such as increasing the compulsory percentage of secondary materials to construction works, triggering the circular building [60]. The implementations of more circular innovations should be motivated by the governmental authorities to explore the potentials, the conditions of success or even the real obstacles for CE propagation. In this way, preparatory steps can be taken for the fully-fledged circular construction by 2050 [54].

2.2. Material hub

For the transition towards the CE paradigm, attention should be given to the waste management in the construction sector. One of the current circular innovations are the environmental streets (Milieustraat), found in each municipality, in which citizens transfer their various waste. Those locations are not just waste platforms, but separation and processing are held so there are potentials for useful orientation of materials [62]. Those environmental streets are used basically for downgrading reasons and question arises if they can be transformed into upcycling centers as a CDW management technique [41].

2.2.1. Importance of material hubs for the transition to circular construction sector

The best practice for CDW management entails consideration of all the actors involved in the waste network. The influence of CDW practice cannot be easily estimated because the variety of actors involved in the supply chain hinders the identification of economic impact and environmental value of this management strategy [17].

In conventional waste management, returned materials after collection are stored in the construction site having high risk of damage and relevant cost incurred. The optimal strategy is to store the materials in consolidation centers for the period within which the supply of returned materials (after deconstruction) matches the demand for new materials in large cities. Existence of consolidation centers close by the city centers can be important in stockholding the returned materials in economic aspect, since these centers can facilitate the just in time deliveries involving the better organisation of site and having fewer vehicle routes [17].

The warehousing of returned materials has low impact on the waste management cost of a project. The low impact of waste management on construction project budget does not trigger this strategy implementation. However, the CDW treatment plant has high impact in total waste management cost, in which apart from storage, inspection, classification or recovery procedures of returned products take place [2, 17]. In the body of literature, those centers are referred as city hubs, centralised collection centers, urban distribution centers or urban consolidation centers [56]. From now on, the term "material hub" will be used in the following segments. It is stated that material hubs can improve the recovery rates of materials once there is knowledge about potential clients. So, the material hubs are organised in such a way that the returned materials can be sold just in time to their final orientation [35]. In Almere-Haven Upcycle platform, a project undertaken by the municipality of Almere in collaboration with companies Maton de Rooy, Antea Group and GBN Groep, a Life Cycle Costing analysis (LCC) illustrated up to 23% economic benets [27].

From the environmental perspective, the material hubs can be of high importance. In those facilities, the materials are graded based on their quality. Without grading of returned materials takes place, it is assumed that returned materials can be directed towards lower grade recovery options such as recycling [29]. So upcycling is more possible leading to reducing the waste amount, since returned materials can substitute raw materials. Specifically in plasterboard, up to 15% of material savings were detected [17]. Besides, the material hubs can facilitate the better planning of materials routes in comparison with the distributed system of warehouses. This center can also lessen the CO_2 footprint from materials transportation since the large quantities of returned materials can be stored and transferred in smaller quantities within the city [58]. With the condition that higher upcycling rates are achieved in the hub, the energy required for downgrading activities will be eliminated, so the air quality in cities can be improved [56]. Upon conducting Life Cycle analysis (LCA) in the Almere Upcycle platform, environmental profits from 19% till 78% were detected depending on the various material flows [27].

2.2.2. Material hub characteristics

In the previous section, it became obvious that material hubs could have financial and environmental profits and investigation about their characteristics follows. Not harmonisation of returned materials is leading to different processing techniques in a material hub [17]. Generalisations about the center operations cannot be made without a large number of assumptions because of the aforementioend heterogeneity of returned materials. According to research, visits in material hubs in the Netherlands and exploratory discussions with experts, six main activities are held in the material hub: inspection, sorting, upcycling, preparation for reuse/recycle, reuse or storage [41].

Concerning the capacity in material hub, space is devoted not only for storage but for reception, inspection, separation and the equipment of returned materials [27]. In a relevant research, it was assumed that the material hub space is approximately 2.5 times the volume of returned materials, due to additional space for ventilation and sewage systems required [58]. Regarding the material streams, a method about decision-making followed in "Steiger 113" project is described [27]. Before demolition of projects starts, inventory of materials quantity and quality is undertaken. In the second phase, consideration about how materials can be further processed based on “Ladder van Lansink", mentioned in Section 2.1.2, follows to investigate the highest quality application of returned materials in the region. Different scenarios are made about materials treatment and then final decision among those scenarios is taken based on sustainability requirements and costs involved from the demolition till the final destination of returned materials [27].

2.3. Decision-making in material hub

In Operation Research (OR) literature, multi-criteria decision-making problems about waste management, like the decision-making process followed in "Steiger 113" project, are addressed [52]. Specifically, numerous scientific papers put particular emphasis on formulation and solution methods for problems pertaining to supply chains in waste management. In this section, a review of recent publications relevant to supply chain network models based on OR techniques is entailed, with the main focus on RL models. Depending on the model specificities, the scientific papers are divided into the following categories: environmental objectives, uncertainties in quality categorisation of returned materials, uncertainties in quantity of returned materials and supply chain network design. Table in Appendix A illustrates the basic characteristics in supply chain models reviewed and the specificities of this study.

2.3.1. Environmental objectives in Reverse Logistics model

Various scientific studies developed RL models with environmental goals, apart from financial. The environmental objectives mainly evolve around generating renewable energy or minimising the greenhouse gas (GHG) emissions in the transportation of materials and the operation in supply chain procedures [1].

Specifically, Fathollahi-Fard & Hajiaghaei-keshteli developed a two-stage stochastic multi-objective CLSC model with three objectives of downsizing risk of unfavorable scenarios, minimising cost and environmental impacts [14]. The Recipe 2008 database in ECO-it software was used to calculate the environmental impact in constructing facilities, processing and transferring materials in different facilities. Heuristic and metaheuristic algorithms were used as solvers and this model was tested in a glass industry case. Moonen focused on CE in RL and particularly, proposed a mixed integer linear programming (MILP) model determining the optimal proportion of materials from one dismantled asset which will be reused and recycled in a cost-effective way [40]. The quantity and quality of demand and supply were assumed as certain and the time during the processing facilities and transportation was neglected. This model was applied in two cases of infrastructure materials. Zhou, Cai, Xiao, Chen & Zeng developed a RL linear programming (LP) model based on the value flow analysis of CE to find a balance between economic and environmental benefits [65]. This value of flow concept is relevant with the efficient use of resources, loss of waste value, environmental damage value and resource value added. This model was redesigned to be applied in a scrap recycling business to integrate circularity by reducing the costs involved.

2.3.2. Uncertainties in Reverse Logistics model

The majority of papers have deterministic parameters. Recently, research has been conducted in integrating inherent uncertainty in the RL network models because of the high level of complexity. Demand rate in quantity and quality is involving uncertainty but the most important ambiguity is detected in the collection of returned materials regarding their volume, quality and timing [35].

Li et al. proposed a generally applicable multi-product multi-period RL model in which a collection point in a close distance from the customers was selected under uncertain quantity and quality rate of returned components and materials [35]. Those uncertain parameters were modeled as fuzzy parameters and the objective was to maximise the profit from the value recovery of returned products within a certain time horizon. The model was applied in a case of electrical home appliances. Kim, Do, Kang & Jeong developed a robust optimisation model with uncertainty in the supply rate of returned materials and the demand for potential clients [32]. This research was conducted in the fashion industry supply chain and the end-of-life cycle products were collected by repairers, remanufacturers or recyclers so they could be reintroduced in the supply chain. It was concluded that depending on the industry, different recovery options could be selected. Liao formulated a general multi-echelon mixed integer non-linear programming (MINLP) RL network model by considering different recovery processes of recovered products (repair, remanufacturing, recycling, reuse, incineration) [36]. The proposed model was tested in recycling bulk waste case and a sensitivity analysis of changing demands rate and capacity of the processing facilities was conducted to assess the model's performance under uncertainty. John et al. developed a multi-product multi-echelon MILP RL model with grading the returned materials and accordingly transferring them in suitable recovery facilities (recycling, repairing and remanufacturing) [29]. The quality of materials was categorised based on their potential residual values by formulating scenarios and the model was applied in mobile phones and digital cameras. The main aim was to determine the optimal number and location of different facilities to be opened and the materials flow through different facilities in the supply chain within the lowest cost. Edalatpour, Al-e-hashem, Karimi & Bahli developed a stochastic multi-product multi-echelon multi-period model with uncertain waste generation rate [11]. The material flow was not determined according to the decision-maker's preferences, but a separation ratio for waste was introduced in each processing facility to categorise the materials and accordingly define their next destination. This model was applied in a case study to help planning and operating the RL activities in a city and by performing sensitivity analysis, managerial insights were attained. Scenario-based LP CLSC network model was developed by Srinivasan & Khan, integrating various products distributed in various facilities during a time horizon considering uncertainty in demand, return, reprocessing, reassembling and disposal rate with objective the minimum cost by trade-off between parts recovered and parts purchased from external suppliers in a cartridge manufacturing company [53]. Shahparvari et al. developed a robust MILP CLSC network in which returned products were collected and recovered in modules in different quality levels to meet the customer's demand, aiming in maximisation of financial benefits [51].

2.3.3. Supply chain network design in Reverse Logistics model

Decisions about the location and capacity of processing facilities are usually made in order to determine the RL network. However, the RL network design cannot be standardised because of the uncertainties involved in RL and mainly the different nature of processed materials [29, 36]. The selection of processing facilities location constitutes one critical decision because of the high cost incurred and relocating those facilities is not an economical wise option [64]. Besides, the location of the structures which will be deconstructed in the future cannot be predicted [55]. In case that the facilities in which the materials will be processed are located in fixed points and the new structures planned to be dismantled will be located in a long distance from those fixed locations, the RL design will be meaningless, in the sense that the logistic costs will be considerably increased. Keeping the distances between the processing facilities and the supply sources in different time periods as small as possible has an important effect in whether the materials will be recovered or not, in the sense that the contractors will prefer to landfill the materials instead of transferring them in remote recovering facilities in order to have fewer expenses [55]. Choices among different numbers and capacities and potential locations of facilities constitute crucial decisions in supply chain design, influencing the final costs [14].

Trochu et al. developed a MILP model with scenarios considering relocating, extending/ closing and opening new processing facilities in the wood waste industry with uncertain parameters the quantity and quality of returned materials and the variable location of supply sources [55]. Scenarios were generated in order to integrate the uncertainty by considering discrete values for each uncertain parameter based on historical data analysis. Yu & Solvang developed a two-stage stochastic bi-objective mixed integer programming (MIP) model providing the option of changing the capacity in the processing facilities (recovery, recycling, remanufacturing and energy recovery centers) under uncertain quantity and quality of different returned products [64]. In this way, this model could be used for processing RL procedures in different materials.

2.3.4. Conclusions

From the literature analysis, it can be concluded that circularity is a concept which has not been integrated into supply chain optimisation models in a standardised way for various construction waste streams. The uncertainty in quantity of materials in supply and demand was tackled in various OR methodologies, while the quality issues of the collected materials has not been addressed in various papers [55]. Assumption about the RL system for decision-making is difficult to be made because of various characteristics of returned materials and the corresponding treatment facilities. In this research, the aforementioned research fields constitute the theoretical framework of the problem postulated and are attempted to be combined.

3

Conceptual framework of model

From the literature review conducted, it is deduced that heterogeneity of material characteristics results in different recovery activities and Reverse Logistics (RL) can be designed in a different way. This study assumes a RL environment which entails procedures and facilities which can be generally applied in different clusters of materials. Moreover, this chapter elaborates the key aspects, cost components and circularity dimensions which are taken into consideration in the problem.

3.1. Material clusters

Management of a material hub is not only related to inventory of a single product from a single geographical location. Inventory systems have to treat many products taken from disperse geographically locations. One simplification could be to apply an appropriate single-product model to each of the products individually in order to face the multiple products management. However, there are some interactions between the materials, such as production, treatment or transportation at the same time. Once this interaction is not substantial, an approximation of single-product model can be used with the assumption of a single-product inventory model. Otherwise, multi-product inventory models should be developed [24]. In the problem defined, interrelationships of how the materials can be treated, stored or downgraded in the material hub are incorporated.

Generally, the Construction and Demolition waste (CDW) varies in characteristics depending on its origin. For instance, the deconstruction of a road can lead to the production of excavated materials, while the demolition of a building can produce large quantity of waste concrete. Each construction structure and technique can generate different range of material waste, as indicated in the Table 3.1. Subsequently, this heterogeneous character of CDW hinders the formulation of a specific treatment of all the waste materials and structures [17].

Table 3.1: Construction and Demolition Waste composition [17]

Waste Category	**%, min-max range**
Concrete and Masonry	40-84
Concrete	12-40
Masonry	8-54
Asphalt	4-26
Others (mineral)	2-9
Wood	2-4
Metal	0.2-4
Gypsum	0.2-0.4
Plastics	0.1-2
Miscellaneous	2-36

Materials, such as concrete, wood, metal, gypsum board, building materials packaging cartons, plastic, asphalt and debris are most often detected in the CDW [16]. A research conducted in the Metropolitan Region of Amsterdam (MRA), in which materials (1.400.000 tons of construction and demolition waste) in 500 building were registered after demolition. Based on the occurrence and quantity of materials found, fifteen material clusters were defined: sand and soil, concrete, bricks, stones, ceramics, glass, gypsum, steel and iron, copper, other metals, wood, paper, plastics, bitumen, and isolation material [38]. It is assumed that those material clusters can be recorded in other municipalities in the Dutch building context and will fall within the scope of the current research.

3.2. Reverse Logistics environment

The RL environment considered in this study, is based on the waste wood material flow designed by Trochu et al. [55] and the generally applicable closed loop supply chain assumed by Fathollahi-Fard & Hajiaghaei-keshteli [14]. Following an exploratory discussion with experts about current RL practices in Haarlem Municipality, the RL system is adjusted accordingly [57].

In specific time periods within a certain time horizon, different assets owned by the municipality are reaching their end of life cycle, so they should be deconstructed. It is assumed that the demolition company transfers the ownership of returned materials in the municipality after the deconstruction. There is information about the location and time the returned materials can be available. However, there is uncertainty about the quantity and quality of returned materials from the demolished projects. Those characteristics will be assumed according to experts opinion.

3.2.1. Circularity aspect

In the demolition sites, the products are dismantled either on component or material level. In this study, the structures are deconstructed in materials-base and not in component-base and clustered in the fifteen material categories defined in Section 3.1.

The returned materials are collected in a centralised collection center (material hub). This hub is owned by municipality and the optimal capacity of this hub is under investigation. In the hub, the returned materials are categorised according to their quality. This quality grade will correspond to certain circular recovery options for returned materials, so accordingly the materials will be transferred to clients after the hub. This grading may generate more cost but in this way the optimal decision for the recovery option of the returned product can be defined [29]. The recovery options are reusing, remanufacturing and recycling which were selected based on the R_3, R_4 and R_5 circular activities in R-ladder, which was described in the Chapter 2. Concerning the quality categories, returned materials which can fulfill their original function are in grade G_1 (R_3) and can be reused directly in new construction projects. Returned materials which can be used in manufacturing a new product with the same function are in grade G_2 (R_4) and required by remanufacturers. Returned materials which can be processed to obtain the same or lower quality are encompassed in grade G_3 (R_5) and required by recyclers. The returned materials with no residual value are in grade G_4 and are disposed to landfills. So, the quality grades can be directly translated to quality of materials required in demand nodes (new construction projects, remanufacturers, recyclers and landfilling facilities).

Regarding the RL environment assumed, certain clarifications follow. In reality, after the remanufacturing and recycling facilities, returned materials can be converted into products ready for use in the new construction projects or can be further processed in the manufacturing facilities (which are named as outsourcing suppliers in the current study). Additionally, returned materials might be transferred to demand nodes outside the municipality range. However, since this model is developed to create a framework for the municipality to evaluate the contribution of the material hub as a waste management technique in the local circular construction market and the remanufacturers and recyclers are considered as external actors in the RL environment, those material flows will not be considered in the problem concept. It should be also mentioned that inspection of materials can also take place in the demolition site and accordingly the returned materials can be directly transferred in the correspondent customers. However, it is assumed in the problem that the inspection of materials takes place only in the material hub, so the material streams in which the returned materials are transferred directly from the demolished projects to relevant demand nodes will be omitted in the proposed system. All the returned materials are transferred in the hub and after inspection and categorisation are shipped in the correspondent demand nodes, even though this assumption might lead to additional cost of transferring the materials through the hub.

The way the circularity will be embedded in the research is inspired by the integration of the value flow analysis of Circular Economy (CE) in the concept of RL developed by the research team led by Professor Xu Xiao [65]. The fundamental principles of the value flow analysis of CE in RL are about merging environmental values and economic profits. Particularly, the overall value is calculated by finding the summation of value of efficient use of resources (value for less environmental damage by recourse utilization and depletion of new resource production), the loss of value of materials with no further utility and the value of environmental damage from RL operations [65].

Within this context of value flow analysis, RL operations can be associated with two contradicting CE dimensions. On the first hand, RL is accounted as resource saving and waste minimisation, but on the other hand, RL operations, such as remanufacturing and recycling, can lead to secondary pollution and environmental deterioration [65]. In order to translate those conflicting circularity dimensions (from the municipality perspective) in the model, two functions are defined for the local construction market. Initially, the first term is circularity which is formulated in function of the percentage of returned materials which covers demand of materials in new projects. Moreover, the second aspect is interpreted as the CO_2 emissions from transportation of materials from node to node in the network assumed and the CO_2 emitted in each facility in the network multiplied with each material quantity processed.

3.2.2. Decisions

Initially, decision is taken about the quantity of returned materials after demolished projects which is transferred in each quality grade in the material hub.

In a second phase, the optimal decision of whether the returned materials are immediately transferred in the demand nodes (new construction projects, remanufacturers recyclers and landfills) or 'downgraded' in the directly following lower quality grade or stored is taken. The option of upgrading is not possible in this facility, whereas storage is only possible for returned materials categorised in grade G_1 to cover the demand of materials in new construction projects.

In reality, downgrading of materials means that materials are further processed and transformed in lower value products, but it should be clarified that in the current research, 'downgrading' means that materials are sold in a lower price than the price they could have been sold according to their quality grade.

One case is illustrated to provide an example. Following the inspection, the returned materials are categorised in quality grade G_1. At this point a decision should be taken in the hub about either transferring the materials in the new construction projects or in case there is no demand for returned materials in the new construction projects storing them or selling them in the lower purposes demand nodes according to the R-ladder hierarchy respectively.

The aim of the model is to create a local circular construction market between demolished projects and the new construction projects within a certain time horizon. However, in case the demand in the new construction projects cannot be covered only by returned materials, decision should be taken about quantity of materials which should be purchased by outsourcing suppliers (like demolition projects outside the municipality or new manufacturers within municipality).

3.2.3. Time periods

Because of variability in supply and demand of returned materials in different time periods, the demand and supply rate are integrated into periodic base in the current study, assuming small uniform time intervals to simulate the continuous periodic level. The choice of the time intervals depends on the data availability and the time periods that projects are planned to be demolished and constructed. The demand for the respective periods should be met by the end of each time interval.

3.2.4. Cost components

Cost components in material hub

In order to have a sound picture of costs related to the material hub, cost components in facilities which have the function of inventory were reviewed. The costs related to the material hub are inspired by the inventory management theory entailed in the Appendix B and in the following section, it is presented whether the cost components are applicable in the current study or not.

1. Cost of ordering:

   In the specified problem, the returned materials are owned by the municipality, since the projects which are planned to be demolished are owned by the municipality. So this cost is not integrated in the scope of the research.

2. Holding cost:

   In the current study, the holding cost encompasses all the costs involved in the storage of materials until they are transferred in the demand nodes. There are two types of holding cost in the problem assumed: holding cost within the same time period and within two consecutive time periods. Specifically, there is holding cost for materials which are kept in the hub in the same quality grade until are transferred to the demand nodes at the end of the same time period and there is the holding cost for materials categorised in grade G_1 which are stored in the hub until the next time period. For the shake of simplicity, the first cost is named as operational cost and the second one as storage cost.

3. Shortage cost:

   This cost refers to the cost incurred from the unsatisfied demand of materials in a specific time period due to limited inventory of materials. In this research, in case that demand in each time period is not met by returned materials, it is covered by purchasing new materials from outsourcing facilities. So, this cost is not applicable in the problem assumed.

4. Revenues from sales:

   In order to motivate the circular dimensions in waste management, the cost of waste treatment should be correlated with the cost savings from recycling and reusing of waste generated [17]. The problem assumed is developed from the perspective of the municipality, meaning that the municipality owns the hub and the projects which will be constructed, so there is no actual financial transaction once the materials are reused in new projects. However, the municipality can achieve revenues by selling the returned materials to potential clients (remanufacturers and recyclers). So, this profit is represented into the model.

5. Salvage value:

   This value is relevant to the materials in inventory which are sold with discount in market in case there is no demand for them in a specific time period. In the problem postulated, there is the option of 'downgrading' the returned materials under no demand circumstances, which means that the returned materials are sold in a lower price than the price they could have been sold according to their initial quality grade. This salvage value is identical with the price the returned material are sold to remanufacturers and recyclers, so it is not added as a separate cost component.

6. Lead time:

   The cost related to lead time pertains the procedure between receiving and delivering the order in demand points. It is assumed that this expense is entailed in the transportation costs. For this reason, it is not incorporated as additional cost component in the problem defined.

7. Facility operating costs:

   The fixed cost of opening a hub is neglected from the model, since this cost cannot influence the optimal decision of material flows and increase the level of complexity in the software solution. In the model developed, the remaining costs (cost of renting/ buying equipment, paying labor for inspection/ categorisation/ maintenance/ storage) are incorporated in the holding cost.

General cost components

1. Cost of buying materials from outsourcing facilities:

   For different materials, the aforementioned cost components can vary.

2. Cost of taxes to dispose the returned materials with no further utility in the landfills.

3. Transportation costs between the facilities:

   It is assumed that there is no substantial difference in the distances between nodes within the municipality scale. Subsequently, the distance between nodes is omitted and an average transportation cost is assumed per quantity of materials transferred.

4

Solution Methodolgy

In this section, the methodology used to provide a solution to the problem defined is entailed. Specifically, it is explained how the actual problem is simulated as an optimization model. Due to the complexity of the Reverse Logistics (RL) problem and the subjectivity in the data availability, approximations in the model inputs are unavoidable and are described in this chapter. In the last segment, the solution steps are illustrated to investigate the circumstances under which a material hub is a sound decision.

4.1. Optimization Model

In this research, the problem identified requires integration of the processes occur in the different facilities, so it is selected to configure the system in a mathematical programming model. Particularly, an optimization model is formulated based on inventory and minimum cost flow models in Linear Programming (LP) theory, elaborated in the Appendix B.

The goal of the model developed is the minimisation of cost in the flow of returned materials in the RL procedures through a material hub within the municipality scale, aiming in circularity goals and decreasing the CO_2 rates in the same time. The problem developed is tackled as three objective multi-product multi-period LP problem and solved with the ε-constraint method.

Each objective function will be expressed as a mathematical function including the decision variables, which represent the decisions that should be made in the system defined and are relevant to the quantity of material flows between the facilities included in the RL network assumed. The decision variables should be selected in a way to optimise the objective functions and are subjected to certain constraints, which are relevant to the capacity in the material hub, flow conservation of material flows between the facilities and the satisfaction of materials demand. Additionally, the decision variables in the objective function and the constraints will be combined with constant numbers as inputs in the model, the parameters, which express the rate in which the decision variables affect the objective functions.

4.2. Uncertainty of model inputs

The model in this research refers to a present decision based on supply-demand trends and prices of materials in the future. Since the future cannot be predicted, some approximations are made.

Within the inventory management and RL theory, there are certain methods to forecast parameters which involve high uncertainty level. Statistical forecasting methods can be used in which a range for uncertain factors can be concluded based on historical trends [33]. Judgmental forecasting methods were developed in which the expert judgment can be used in case that historical data are not available and can be not trustworthy because of large deviations from case to case. However, even if data are available for statistical forecasting methods, the experts' opinion could be preferable. One method among the various judgemental forecasting methods is the managers' opinion to make a forecast based on their experience and knowledge of the current situation [33]. Another methodology which is used in case of limited knowledge is the scenario generation about the uncertain parameter values, which are not based on historical data but are driven by the actual problem.

Based on the aforementioned techniques, the uncertainty in the inputs about supply-demand dynamics and material prices is tackled. Specifically, the supply and demand patterns of materials within the time horizon under investigation are relied on scenarios generation. Concerning the quality of materials derived from the demolition sites, the expert judgement is selected as the most suitable forecasting technique. The material prices are based on records of material prices in 2017 [9]. All the inputs considerations and values are described in detail in Chapter 6.

The procedure of input approximations may involve some risks relevant to the scientific validity of the findings. So, the sensitivity analysis is selected in order to find how a variation of the uncertain parameter values of this study (supply-demand patterns and materials prices) will influence the objective function, substantially or not. In this way, the critical parameters for the final solution are identified [33].

4.3. Solution steps

To provide an answer to the main research question, the circumstances under which the investment of a material hub is a viable decision will be explored in the following solution steps, which are illustrated in Figure 4.1.

1. Initially, the cost involved in the current situation is investigated and considered as a benchmark. The optimal cost incurred from the model will be calculated under various scenarios of supply-demand ratio assuming uniform distributions within the time horizon. Comparison between the current situation and model results is realised in financial terms. The scenarios under which investing in a hub is a cost-effective decision are regarded as candidate solutions for the final optimal decision.

2. The candidate solutions are further assessed by varying the supply-demand dynamics of the aforementioned scenarios within the time horizon and their economic performance is recorded. Because of the random fluctuation of the supply-demand patterns, appropriate sensitivity analysis in those inputs is performed. Comparison between cost involved in the current situation and the candidate solutions is conducted to identify under which instances of supply-demand fluctuations within the predefined scenarios investing in a hub is a sound decision in financial terms.

3. All the candidate solutions are appraised beyond by undertaking a sensitivity analysis in the remaining inputs of the model (capacity and cost components). Once the cost in the current situation is compared with the cost in the candidate solutions, the critical parameters for the model results and the range of those parameters until the material hub is a financially feasible decision are determined.

4. The objective values of circularity rate and $C0_2$ emissions of the candidate solutions found in the previous steps are investigated. To find the optimal solutions in this multi-objective problem with contradicting objectives, the ε-constraint method is carried out in order to formulate the Pareto optimal solutions in each scenario. The decision-makers in the municipality can select the most favored solution among the Pareto optimal solutions of all scenarios.

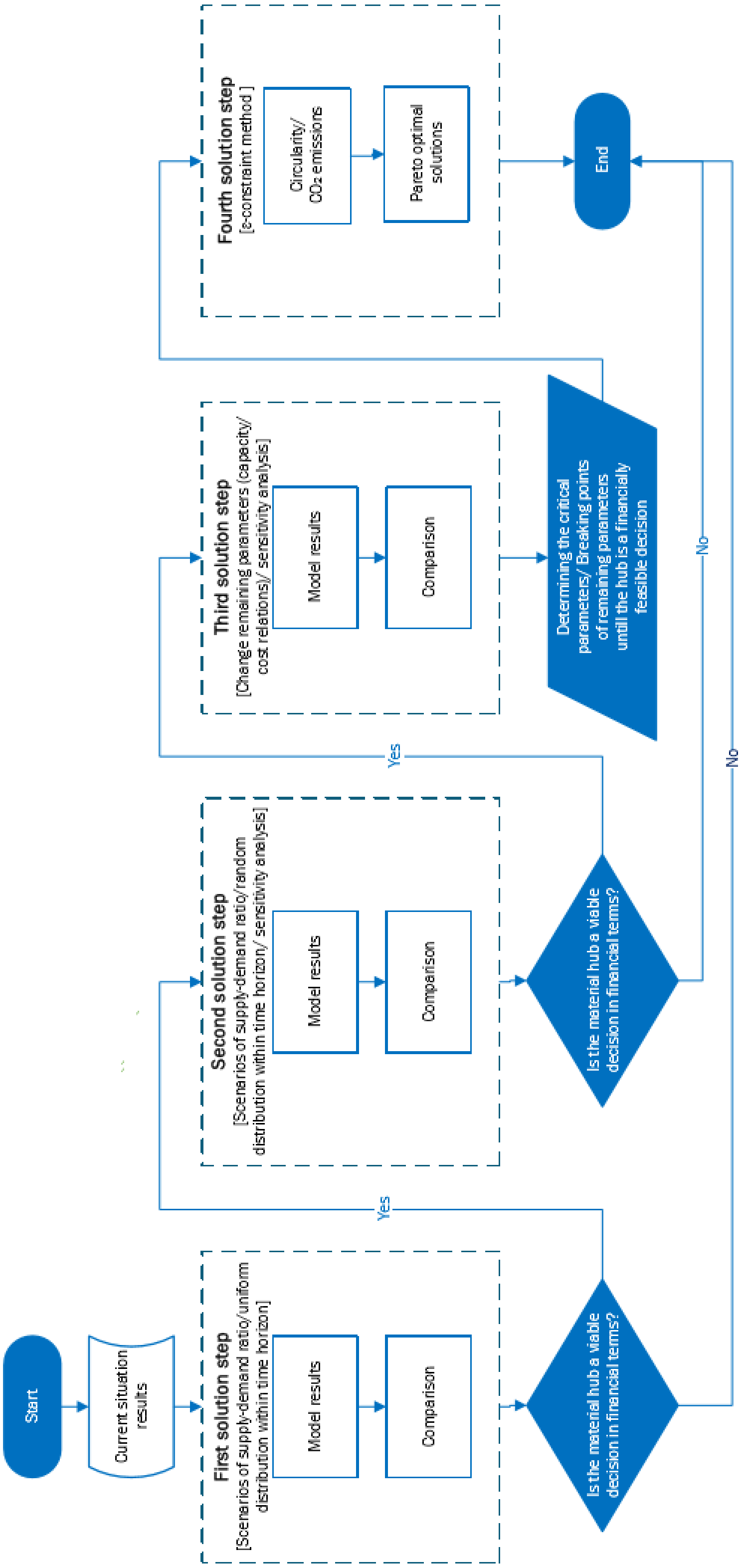


Figure 4.1: Solution steps

5

Model

Initially, the problem is framed in mathematical terms, accompanied by assumptions of the actual problem, whereas the second section of the chapter includes the mathematical model to provide a solution for the problem specified.

5.1. Problem description

We represent supply nodes (either demolished projects or outsourcing facility) by set $s \in S$ ($S = \{1, \dots, p, o\}$) and demand nodes (new construction projects, remanufacturer, recycler and landfilling facility) by set $d \in D$ ($D = \{1, \dots, c, m, r, l\}$). We represent the material hub with a set of nodes which denote the allocation of returned materials in a specific grade $g \in G$ ($G = \{G_1, G_2, G_3, G_4\}$) in the hub. The capacity of the material hub is modeled by arcs. The nodes $i, j \in N$ can be connected with arcs $(i, j) \in$ A as defined in the Figure 5.1.

A directed graph $G(N, A)$ is assumed where $N = S \cup G \cup D$ is the node set, $A = A(S) \cup A(G) \cup A(D)$ is the arc set, where $A(P) = \{(i, j) \in P \cup G | i \in P, j \in G\}$, $A(O) = \{(i, j) \in o \cup C | i = o, j \in C\}$, $A(G_1) = \{(i, j) \in G_1 \cup C | i \in G_1, j \in C\}$, $A(G_2) = \{(i, j) \in G_2 \cup m | i \in G_2, j = m\}$, $A(G_3) = \{(i, j) \in G_3 \cup r | i \in G_3, j = r\}$, $A(G_4) = \{(i, j) \in G_4 \cup l | i \in G_4, j = l\}$, $A(G) = \{(i, j) \in N | i \in G_1, j \in G_2 \ or \ i \in G_2, j \in G_3 \ or \ i \in G_3, j \in G_4\}$.

In order to comply with Circular Economy (CE) goals in the Dutch construction sector, municipalities want to deconstruct the projects $p \in P$ which are reaching their end of life cycle and cover the demand of materials in new projects $c \in C$. In case the demand in new projects $c \in C$ cannot be covered only by returned materials, the municipalities purchase new materials from an outsourcing facility which is denoted by o (like new manufacturers).

The municipalities collect all the returned materials from the demolished projects $p \in P$ in a material hub where inspection and grading of materials quality take place. The quality grades assigned in each material are inspired by the circular activities in R-ladder and correspond to quality demands in potential clients, which are the new construction projects $c \in C$, a remanufacturer m and a recycling facility r. In case of materials with no further utility, the returned materials will be transferred in a landfilling facility l. Particularly, the returned materials are graded in the hub in the following way.

- grade G_1: materials which can be directly reused to new construction projects $c \in C$
- grade G_2: materials which can be repaired in a remanufacturer m
- grade G_3: materials which can be recycled to a recycling facility r
- grade G_4: materials which can be transferred in a landfilling facility l

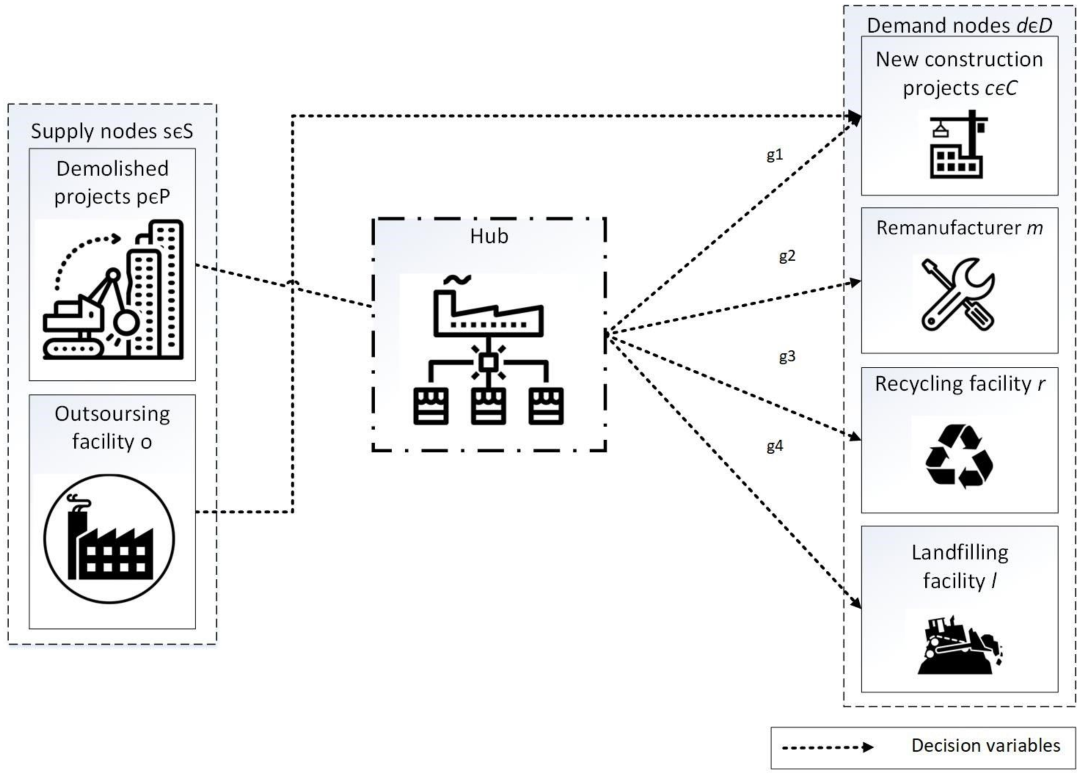


Figure 5.1: Reverse Logistics network [47]

The potentially reusable materials can be hardly reused as products but as secondary building materials, due to possibly no direct demand for them at the time of release [58]. Therefore, in the demolition sites, the products are dismantled on material level and clustered in the material categories $k \in K$ as identified in Chapter 3. We assume that all projects (demolished and new construction projects) are performed in the planning horizon T, which is discretised in t intervals ($t \in \overline{\mathrm{T}} = \{1, \dots, T\}$). This assumption derives from the fact that the exact dates for the execution of projects can vary during the planning horizon T.

Based on the quantity ranges the experts assign for each quality of returned materials collected in the demolished projects $p \in P$, decision should be taken about the exact quantity of materials transferred in each grade $g \in G$ in the hub. Based on the grading of materials in hub, a decision is taken about whether materials will be directly transferred to demand nodes $d \in D$. Otherwise, returned materials are stored (h) or downgraded in the directly lower grade $g \in G$ in hub (to respect the hierarchy of circular treatments in R-ladder) till necessity for them arises in demand nodes $d \in D$. It is possible only to store returned materials of grade G_1, so materials of lower grades (G_2, G_3, G_4) can be either directly transferred to demand nodes $d \in D$ or be downgraded $g \in G$. The operations in the material hub are illustrated in the Figure 5.2. After defining the quantity of returned materials being reused in the new projects $p \in P$, the quantity of new materials from outsourcing node o should be decided.

To simplify the model, we make the following assumptions.

- There are multiple outsourcing facilities, remanufacturers, recyclers and landfills for each material category, but only one node will represent the outsourcing facilities, the remanufacturers, the recyclers and the landfills for all type of materials.
- There is no flow of materials between same entities.
- Each type of waste material should be treated with same technology.
- Storage capacity in hub corresponds to the capacity for returned materials in category G_1.
- The option of upgrading is not possible in this facility.

- Downgrading is defined as selling materials in the price of lower quality than the initial quality grade of materials. No further process of materials takes place in the hub.

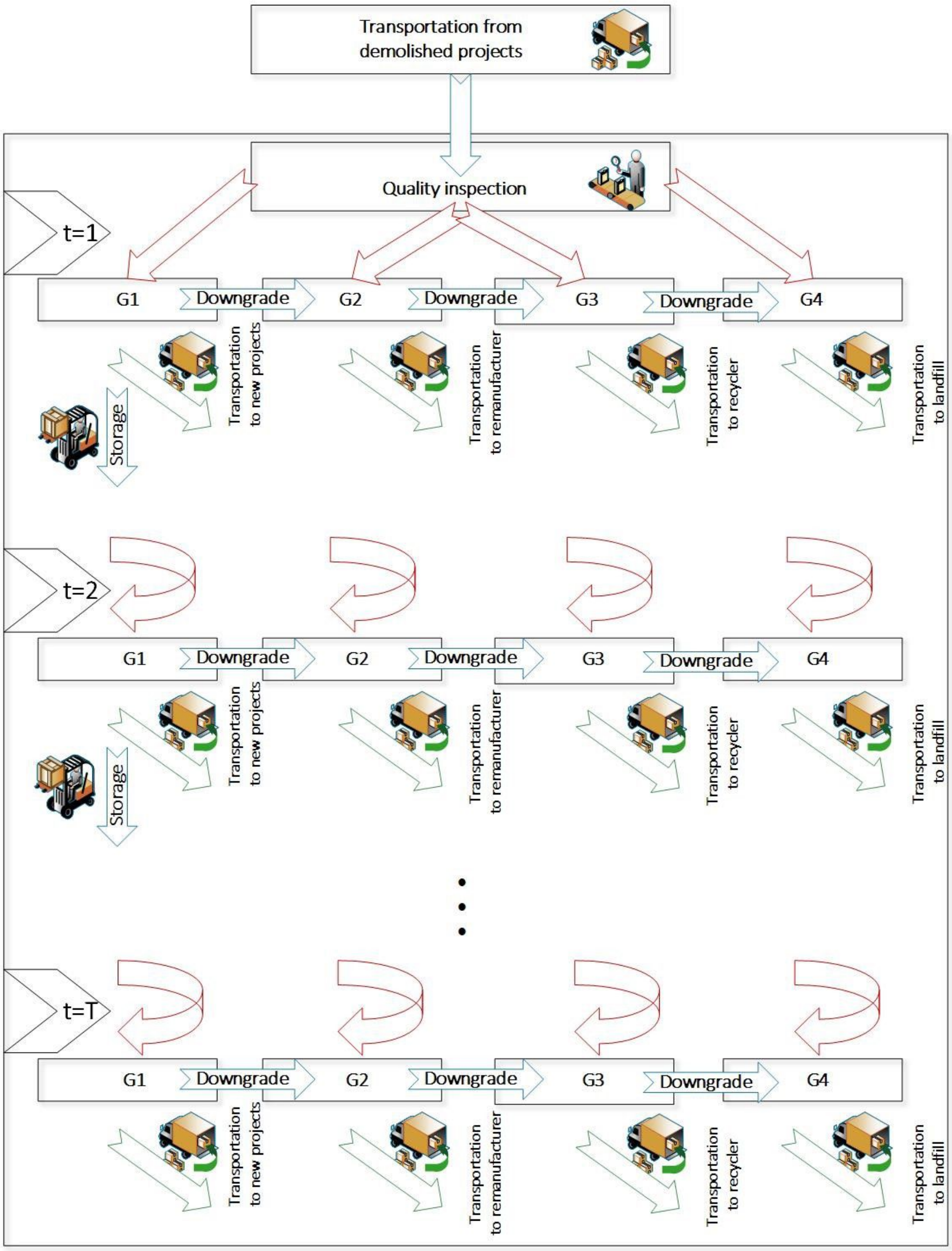


Figure 5.2: Operations in the material hub [47]

The first objective is to seek the flow over time that satisfies all demands defined and obeys all holding inventory capacity constraints at each time step within the time horizon while minimizing total inventory and transportation costs minus the revenues. The second objective is maximizing the circularity rate in the material flow which is interpreted as the quantity of materials reused divided by the whole demand of materials in the new construction projects. The last objective is associated with minimizing the $C0_2$ emissions involved in the whole RL phase (inventory, transportation and treatment of materials).

In essence, the decision-maker faces the three-objective problem of simultaneously minimizing cost, maximising circularity level and minimising $C0_2$ emissions. The objective of this research is to provide the decision-maker with a set of Pareto-optimal solutions that integrate these conflicting objectives. The problem will be solved with the ε-constraint method.

5.2. Mathematical programming formulation

Table 5.1: Superscripts

Superscripts	
p	Demolished projects
o	Outsourcing facility
s	Supply nodes (demolished projects, outsourcing facility)
c	New construction projects
m	Remanufacturer
r	Recycler
l	Landfilling facility
d	Demand nodes (new construction projects, remanufacturer, recycler, landfilling facility)
h	Holding inventory in hub (capacity for materials in grade G_1)
k	Material category

Table 5.2: Sets

Sets	
$i, j \in N$	Nodes in network
$s \in S$	Set of nodes representing supply $S = \{1, \dots, p, o\}$ p: set of nodes representing the materials released from the demolished projects o: node representing the materials bought from outsourcing node
$d \in D$	Set of nodes representing demand $D = \{1, \dots, c, m, r, l\}$ c: set of nodes representing materials directly reused to new construction projects m: node representing materials repaired in remanufacturer r: node representing materials recycled to recycling facility l: node representing materials transferred in landfilling facility
$g \in G$	Set of nodes representing quality grades $G = \{G_1, G_2, G_3, G_4\}$ of returned materials in hub. Based on the hierarchy of circular activities in R-ladder, the grades are assigned to returned materials in the following way. • G_1: materials to be directly reused to new construction projects c • G_2: materials to be repaired in remanufacturer m • G_3: materials to be recycled to recycling facility r • G_4: materials to be transferred in landfilling facility l
$k \in K$	Set of material categories
$t \in T$	Set of time intervals t in the planning horizon T

Table 5.3: General Parameters

General Parameters	
Q_{it}^{pk}	Quantity of returned materials of category $k \in K$ collected in demolished projects $i \in P$ in period $t \in T$
Q_{it}^{ck}	Quantity of returned materials of category $k \in K$ required in new construction projects $i \in C$ in period $t \in T$
min_{ij}^{pk}	Minimum percentage of returned materials of category $k \in K$ transferred from demolished projects $i \in P$ to each grade $j \in G$ in hub
max_{ij}^{pk}	Maximum percentage of returned materials of category $k \in K$ transferred from demolished projects $i \in P$ to each grade $j \in G$ in hub
$Cap_{g_1}^{hk}$	Holding inventory capacity in hub (in quality grade $i \in G_1$) for all returned materials of category $k \in K$
$unit_{g_1}^{hk}$	Standard number of units of inventory capacity for each returned material of category $k \in K$
ε_1	Certain percentage of optimal value of f_1 which should not be sacrificed to improve f_2, f_3
ε_2	Certain percentage of optimal value of f_2 which should not be sacrificed to improve f_3
f_1'	Optimal value of objective function f_1
f_2'	Optimal value of objective function f_2

Table 5.4: Cost Parameters

Cost Parameters	
$\dot{C}_{it}^{ok}$	Cost (per unit) of buying materials of category $k \in K$ from outsourcing facilities o
$\dot{C}_{it}^{hk}$	Holding inventory cost h (per unit) of returned materials of category $k \in K$ in hub
$\dot{P}_{it}^{ck}$	Revenues (per unit) of returned materials of category $k \in K$ in new construction projects $i \in C$
$\dot{P}_{it}^{mk}$	Revenues (per unit) of returned materials of category $k \in K$ in remanufacturer m
$\dot{P}_{it}^{rk}$	Revenues (per unit) of returned materials of category $k \in K$ in recycler r
$\dot{C}_{it}^{lk}$	Cost of landfilling taxes l (per unit) of returned materials of category $k \in K$
T_{ijt}	Transportation cost (per unit) of returned materials between different nodes $i, j \in N \mid i \in P, j \in G\ or\ i \in G, j \in D$

Table 5.5: $C0_2$ Parameters

$C0_2$ Parameters	
CO_i^{ok}	$C0_2$ emissions (per unit) of production materials of category $k \in K$ in outsourcing facilities o
CO_i^{hk}	$C0_2$ emissions (per unit) for holding h returned materials of category $k \in K$ in hub
CO_i^{ck}	$C0_2$ emissions (per unit) of returned materials of category $k \in K$ in new construction projects $i \in C$
CO_i^{mk}	$C0_2$ emissions (per unit) of returned materials of category $k \in K$ in remanufacturer m
CO_i^{rk}	$C0_2$ emissions (per unit) of returned materials of category $k \in K$ in recycler r
CO_i^{lk}	$C0_2$ emissions (per unit) of returned materials of category $k \in K$ in landfilling facility l
CO_{ij}	$C0_2$ emissions in transportation (per unit) of returned materials between different nodes $i, j \in N \mid i \in P, j \in G\ or\ i \in G, j \in D$

Table 5.6: Decision Variables

Decision Variables	
x_{ijt}^{pk}	Quantity of returned materials of category $k \in K$ transferred from demolished projects $i \in P$ to each grade $j \in G$ in hub in period $t \in T$
$x_{ijt}^{(g \to d)k}$	Quantity of returned materials of category $k \in K$ transferred from each grade $i \in G$ in hub to demand nodes $j \in G$, $D = \{1, \dots, c, m, r, l\}$ in period $t \in T$
$x_{ijt}^{(g \to g)k}$	Quantity of returned materials of category $k \in K$ downgraded from quality grade $i \in G_i$ to quality grade $j \in G_{i+1}$ in period $t \in T$
x_{ijt}^{hk}	Quantity of returned materials of category $k \in K$ stored in quality grade $i \in G_1$ in period between $t-1 \in T$ and $t \in T$
x_{ijt}^{ok}	Quantity of new materials of category $k \in K$ transferred from outsourcing node o in new construction projects $j \in J$ in period $t \in T$

Objective functions:

$$\begin{aligned} f_1 = min \quad & \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in D} \dot{C}_{it}^{hk} x_{ijt}^{(g \to d)k} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G_i} \sum_{j \in G_{i+1}} \dot{C}_{it}^{hk} x_{ijt}^{(g \to g)k} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G_1} \sum_{j \in G_1} \dot{C}_{g_1 t}^{hk} x_{ijt}^{hk} \\ & - \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in C} \dot{P}_{it}^{ck} x_{ijt}^{ck} - \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in m} \dot{P}_{it}^{mk} x_{ijt}^{mk} - \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in r} \dot{P}_{it}^{rk} x_{ijt}^{rk} \\ & + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in l} \dot{C}_{it}^{lk} x_{ijt}^{lk} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in o} \sum_{j \in C} \dot{C}_{it}^{ok} x_{ijt}^{ok} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in P} \sum_{j \in G} T_{ijt} x_{ijt}^{pk} \\ & + \sum_{t \in T} \sum_{k \in K} \sum_{i \in o} \sum_{j \in C} T_{ijt} x_{ijt}^{ok} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in D} T_{ijt} x_{ijt}^{(g \to d)k} \end{aligned} \tag{5.1}$$

$$f_2 = max \quad \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in C} \frac{x_{ijt}^{ck}}{Q_{it}^{ck}} \tag{5.2}$$

$$\begin{aligned} f_3 = min \quad & \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in D} CO_i^{hk} x_{ijt}^{(g \to d)k} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G_i} \sum_{j \in G_{i+1}} CO_i^{hk} x_{ijt}^{(g \to g)k} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G_1} \sum_{j \in G_1} CO_{g_1}^{hk} x_{ijt}^{hk} \\ & + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in C} CO_i^{ck} x_{ijt}^{ck} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in m} CO_i^{mk} x_{ijt}^{mk} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in r} CO_i^{rk} x_{ijt}^{rk} \\ & + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in l} CO_i^{lk} x_{ijt}^{lk} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in o} \sum_{j \in C} CO_i^{ok} x_{ijt}^{ok} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in P} \sum_{j \in G} CO_{ij} x_{ijt}^{pk} \\ & + \sum_{t \in T} \sum_{k \in K} \sum_{i \in o} \sum_{j \in C} CO_{ij} x_{ijt}^{ok} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in G} \sum_{j \in D} CO_{ij} x_{ijt}^{(g \to d)k} \end{aligned} \tag{5.3}$$

Subjected to the following constraints:

1. Demand satisfaction : The demand for materials in new construction projects $j \in C$ are fully satisfied by returned materials categorized in quality $i \in G_1$ in hub or by purchasing materials from outsourcing facility o during each period $t \in T$.

$$\sum_{i \in G_1} \sum_{j \in C} x_{ijt}^{(g_1 \to c)k} + \sum_{i \in o} \sum_{j \in C} x_{ijt}^{ok} = \sum_{i \in C} Q_{it}^{ck} \quad \forall k \in K, t \in T \tag{5.4}$$

2. Uncertainty in materials quality at supply nodes : The quantity of each grade of returned materials of category $k \in K$ transferred from demolished projects $i \in P$ to each grade $j \in G$ in hub during each period $t \in T$ will be within a lower and upper boundary according to experts opinion.

$$min_{ij}^{pk} Q_{it}^{pk} \le \sum_{j \in G} x_{ijt}^{pk} \le max_{ij}^{pk} Q_{it}^{pk} \quad \forall i \in P, k \in K, t \in T \tag{5.5}$$

3. Inventory tracking in quality grade G_1 in material hub : The quantity transferred from demolished projects $i \in P$ to grade $j \in G_1$ should be equal to quantity which is stored (h) in grade G_1 and the quantity which is downgraded from grade $i \in G_1$ to grade $g \in G_2$ and the quantity transferred from grade $i \in G_1$ to new construction projects $j \in C$ at the end of each time period $t \in T$.

$$\sum_{i \in P} \sum_{j \in G_1} x_{ijt}^{pk} = -\sum_{i \in G_1} \sum_{j \in G_1} x_{ij(t-1)}^{hk} + \sum_{i \in G_1} \sum_{j \in G_1} x_{ijt}^{hk} + \sum_{i \in G_1} \sum_{j \in G_2} x_{ijt}^{(g_1 \to g_2)k} + \sum_{i \in G_1} \sum_{j \in C} x_{ijt}^{(g_1 \to c)k} \quad \forall k \in K, t \in T \tag{5.6}$$

4. Capacity constraint in hub: The quantity of all materials which is stored (h) in grade G_1 should be less than equal to the whole inventory capacity in the hub at the end of each time period $t \in T$.

$$\sum_{k \in K} \sum_{i \in G_1} \sum_{j \in G_1} x_{ijt}^{hk} \leq Cap_{g_1}^{hk} \quad \forall t \in T \tag{5.7}$$

5. Unit capacity constraint in hub: The quantity of each material which is stored (h) in grade G_1 should be less than equal to standard number of units of inventory capacity in the hub at the end of each time period $t \in T$.

$$\sum_{i \in G_1} \sum_{j \in G_1} x_{ijt}^{hk} \leq unit_{g_1}^{hk} Cap_{g_1}^{hk} \quad \forall k \in K, t \in T \tag{5.8}$$

6. Inventory tracking in quality grade G_2 in material hub : The quantity transferred from demolished projects $i \in P$ to grade $j \in G_2$ should be equal to the quantity which is downgraded from grade $i \in G_2$ to grade $g \in G_3$ and the quantity transferred from grade $i \in G_2$ to manufacturer $j = m$ at the end of each time period $t \in T$.

$$\sum_{i \in P} \sum_{j \in G_2} x_{ijt}^{pk} = \sum_{i \in G_2} \sum_{j \in G_3} x_{ijt}^{(g_2 \to g_3)k} + \sum_{i \in G_2} \sum_{j = m} x_{ijt}^{(g_2 \to m)k} \quad \forall k \in K, t \in T \tag{5.9}$$

7. Inventory tracking in quality grade G_3 in material hub : The quantity transferred from demolished projects $i \in P$ to grade $j \in G_3$ should be equal to the quantity which is downgraded from grade $i \in G3$ to grade $g \in G_4$ and the quantity transferred from grade $i \in G_3$ to recycler $j = r$ at the end of each time period $t \in T$.

$$\sum_{i \in P} \sum_{j \in G_3} x_{ijt}^{pk} = \sum_{i \in G_3} \sum_{j \in G_4} x_{ijt}^{(g_3 \to g_4)k} + \sum_{i \in G_3} \sum_{j = r} x_{ijt}^{(g_3 \to r)k} \quad \forall k \in K, t \in T \tag{5.10}$$

8. Inventory tracking in quality grade G_4 in material hub : The quantity transferred from demolished projects $i \in P$ to grade $j \in G_4$ should be equal to the quantity transferred from grade $i \in G_4$ to landfill $j = l$ at the end of each time period $t \in T$.

$$\sum_{i \in P} \sum_{j \in G_4} x_{ijt}^{pk} = \sum_{i \in G_4} \sum_{j = l} x_{ijt}^{(g_4 \to l)k} \quad \forall k \in K, t \in T \tag{5.11}$$

9. Non negativity constraints for decision variables:

$$x_{ijt}^{pk} \geq 0 \quad \forall i \in P, j \in G, k \in K, t \in T \tag{5.12}$$

$$x_{ijt}^{(g \to d)k} \geq 0 \quad \forall i \in G, j \in D, k \in K, t \in T \tag{5.13}$$

$$x_{ijt}^{(g \to g)k} \geq 0 \quad \forall i \in G_i, j \in G_{i+1}, k \in K, t \in T \tag{5.14}$$

$$x_{ijt}^{hk} \geq 0 \quad \forall i \in G_1, j \in G_1, k \in K, t_j = t_i + 1 \tag{5.15}$$

$$x_{ijt}^{ok} \geq 0 \quad \forall i \in o, j \in C, k \in K, t \in T \tag{5.16}$$

Solution with ε-constraint method:

1. $min f_1 = f_1'$
2. $max f_2 = f_2'$
   subjected to $f_1 \leq f_1' * \varepsilon_1$
3. $min f_3$
   subjected to $f_1 \leq f_1' * \varepsilon_1$
   subjected to $f_2 \geq f_2' * \varepsilon_2$

The model is solved in Python 3.6 using the external library and application programming interface (API) of IBM ILOG CPLEX Optimization Studio Version 12.8.

6

Model inputs

This study contains qualitative and quantitative data, which are either realistic or simulated. The model inputs (general, cost and CO_2 parameters) used in the model implementation will be described in this section.

6.1. General parameters

A time horizon of six years is selected for the validation of the model and divided into four-months periods to simulate the continuous periodic level of each year, resulting in eighteen time periods.

6.1.1. Supply and demand of materials (Q_{it}^{pk} and Q_{it}^{ck})

In this research, information is required about existing projects which are planned to be demolished and future projects which are planned to be constructed. The goal of this section is to generate fake datasets about the projects which will be demolished (supply nodes) and the projects which will be constructed (demand nodes) within the time horizon which can reflect the reality in an acceptable way.

Data provided from research in Metropolitan Region of Amsterdam (MRA) [9] about the quantities of fifteen materials which are released after demolition in Haarlem municipality in 2017 are considered as reference point and entailed in Table 6.1.

Table 6.1: Supply of materials in Haarlem municipality in 2017 [9]

Materials released after demolition of projects			
15 material clusters	**Tonnes per year**	**Tonnes per time period**	**Sum of materials in whole MRA region (tonnes per year)**
sand and soil	14815.00	4938.33	102808.00
concrete	82681.00	27560.33	526947.00
bricks	7092.00	2364.00	53656.00
stones	6457.00	2152.33	59892.00
ceramics	914.00	304.67	6924.00
glass	409.00	136.33	2641.00
gypsum	2610.00	870.00	18286.00
steel and iron	986.00	328.67	6049.00
copper	10.00	3.33	74.00
other metals	175.00	58.33	990.00
wood	2286.00	762.00	18186.00
paper	30.00	10.00	286.00
plastics	84.00	28.00	685.00
bitumen	222.00	74.00	1396.00
isolation material	190.00	63.33	1338.00

Scenarios generation

1. The following scenarios (Table 6.2) of aggregated supply-demand ratio are assigned in all time periods, while the distribution of materials is considered as uniform, meaning that the material quantities are same within the given timeline.

Table 6.2: Scenarios

Scenarios	**Supply /Demand ratio**
1	1:1
2	1:2
3	1:3
4	1:4
5	2:1
6	2:3
7	3:1
8	3:2
9	4:1
10	4:2
11	4:3

2. In the aforementioned scenarios in which results are leading to building the material hub as an economically viable decision, set of instances are generated with fluctuation between the moment the highest values in supply of returned materials and the moment that the highest values in demand for materials are expected.

Specifically, four instances are created in each supply-demand scenario. In the first instance, the material quantities fluctuate according to the following pattern: the highest, average, lowest, average, highest and average value occur in the first, fourth, seventh, tenth, thirteenth and sixteenth period respectively, which symbolize the first period of each year. The second, third and fourth instances follow the same distribution with a phase difference of one year, two years and three years respectively in comparison with the first instance. It is assumed that the average value of material quantities are the reference values in 2017. For each distribution, the average value fluctuates ±50% and the highest value is calculated such that it is three times higher than the minimum value and the sum of all values in supply and demand trends in the whole time horizon is the same across the resulting instances and equal with the sum of the average value of supply and demand of materials during the eighteen periods.

The instances are presented in the Figure 6.1 which shows the value in y-axis that the mean of supply and demand of materials should be multiplied with in each time period. The combination of those instances will generate sixteen instances sets of supply and demand trends, assuming that the highest and lowest points of supply and demand of all fifteen materials happen the same time period. (The materials follow the same trends in supply and demand respectively, meaning that same percentage of material types are released after demolition and same percentage of material types are needed in new construction projects.)

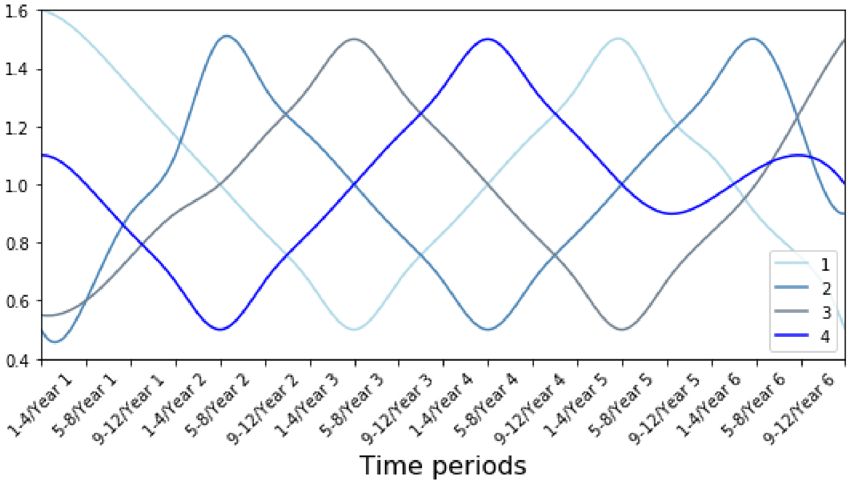
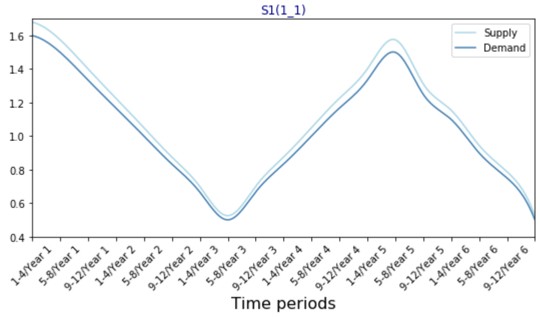
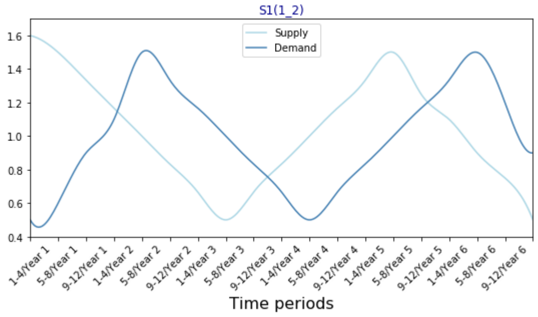
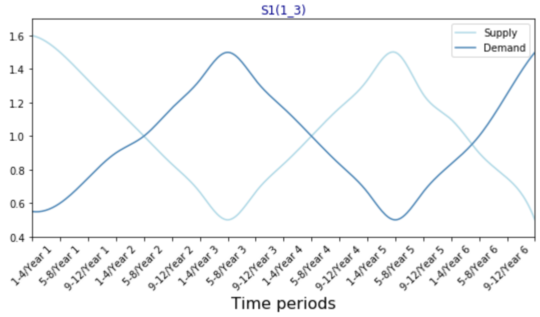


Figure 6.1: Instances

An example is provided for scenario S1. The sixteen sets of instances of supply-demand fluctuation are elaborated in the line plots below (Figure 6.9). Appendix E entails the visualisation of sixteen sets of instances in the remaining scenarios.


S1(1_1)
Supply
Demand
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S1(1_2)
Supply
Demand
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods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Supply
Demand
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
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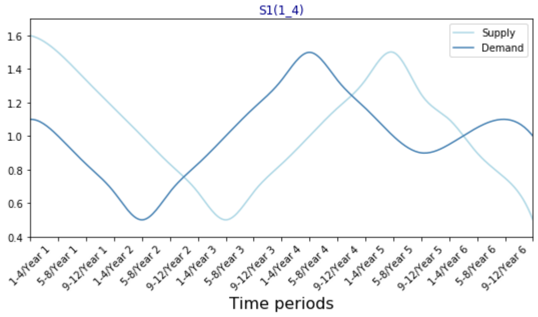
5-8/Year 6
9-12/Year 6
Time periods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Supply
Demand
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1.2
1.4
1.6
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5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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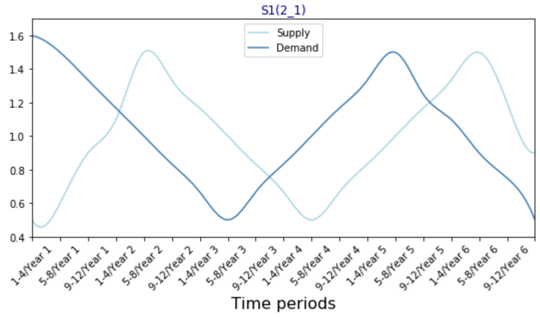
5-8/Year 6
9-12/Year 6
Time periods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Demand
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0.8
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1.2
1.4
1.6
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5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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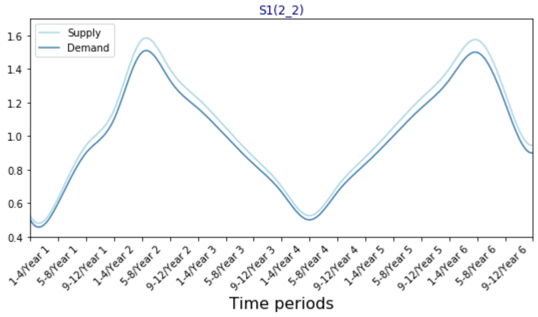
5-8/Year 6
9-12/Year 6
Time periods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Supply
Demand
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0.8
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1.2
1.4
1.6
1-4/Year 1
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9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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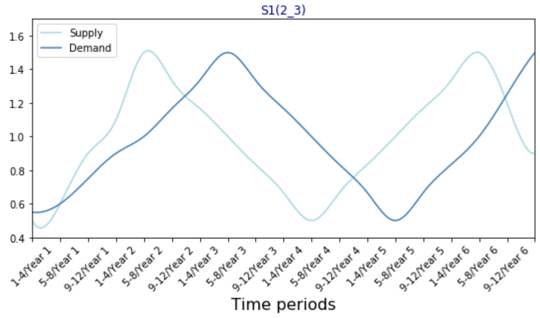
5-8/Year 6
9-12/Year 6
Time periods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Demand
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0.6
0.8
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1.2
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1.6
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9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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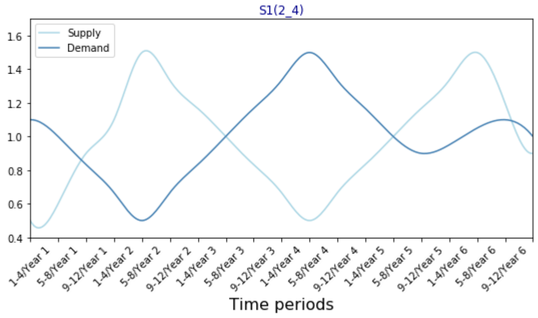
5-8/Year 6
9-12/Year 6
Time periods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Supply
Demand
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0.8
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1.4
1.6
1-4/Year 1
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1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods

Figure 6.9: Sets of instances in scenario S1

Observations about this data generation approach

It should be remarked that the instances are developed not based on specific construction trends but in a way that as many cases of supply and demand dynamics can be simulated. It can be assumed that for each distribution, the average value can fluctuate other than ±50% and the highest, average and lowest values take place not always in the first period of each year but also in the second, third or fourth time period of each year.

6.1.2. Expected materials quality after demolition (min_{ij}^{pk} and max_{ij}^{pk})

Qualitative data are used for estimating the materials quality of fifteen materials after demolition. Based on expert judgements (Appendix D) and assumptions used in MRA research [9], certain ranges of materials which can be reused, remanufactured, recycled and landfilled after the demolition are expected and presented in Table 6.3.

Table 6.3: Expected materials quality after demolition

Material clusters	Percentage of materials which can be reused (%)	Percentage of materials which can be remanufactured (%)	Percentage of materials which can be recycled (%)	Percentage of materials with no further value (%)
sand and soil	80 – 100%	0 – 10 %	10 – 20%	-
concrete	0 – 10%	-	80 – 100 %	0 – 20 %
bricks	0 – 10%	-	80 – 100 %	0 – 20 %
stones	0 – 2%	-	50 – 97 %	0 – 1%
ceramics	0 – 5 %	-	80 – 100 %	0 – 20 %
glass	0 – 10%	-	80 – 100%	0 – 20 %
gypsum	-	0 – 20 %	80 – 100%	0 – 20 %
steel and iron	0 – 20%	0 – 20%	60 – 100 %	0 – 20 %
copper	-	-	80 – 100 %	0 – 20 %
other metals	-	-	80 – 100%	0 – 20%
wood	0 – 10%	0 – 10%	60 – 80%	0 – 20%
paper	-	0 – 10 %	80 – 100%	0 – 20%
plastics	0 – 50%	-	20 – 50 %	20 – 80 %
bitumen	0 – 20%	-	80 – 100%	0 – 20 %
isolation material	-	-	0 – 20 %	80 – 100%

Because of those subjective expectations of the materials quality, a symmetric triangular distribution for those parameters is integrated into the model, using the ranges in Table 6.3 as minimum and maximum values in the distribution function.

6.1.3. Capacity ($Cap_{g_1}^{hk}$) and Unit of Capacity ($unit_{g_1}^{hk}$)

The maximum quantity of materials which can be stored is estimated by multiplying the maximum percentage which can be reused according to experts judgement (Appendix D) with the quantities of fifteen materials in 2017 (from MRA report [9]). The maximum quantity which can be stored is considered as the whole hub capacity. It is observed that the maximum quantity of ceramics, glass, plastics and bitumen are approximately the same quantity. This quantity is assumed to be the basic unit of capacity and depicted in all scenarios of supply-demand ratio in Table 6.4.

Based on the maximum quantity of materials which can be stored, it is assumed that each material consumes a standard number of basic units of capacity in all scenarios and illustrated in Table 6.5.

Table 6.4: Basic Unit of Capacity in each scenario

Scenarios	Basic Unit of Capacity (tonnes)
1, 2, 3, 4	15
5, 6	30
7, 8	45
9, 10, 11	60

Table 6.5: Standard number of basic unit of capacity for fifteen materials

sand and soil	**concrete**	**bricks**	**stones**	**ceramics**	**glass**	**gypsum**	**steel and iron**
330	183	15	3	1	1	0.1	4
copper	**other metals**	**wood**	**paper**	**plastics**	**bitumen**	**isolation material**	
0.1	0.1	5	0.1	1	1	0.1	

6.1.4. Rates for ε-constraint method (ε_1 and ε_2)

The selection of rates ε_1 and ε_2 is explained in Section 7.4.

6.2. Cost parameters

In the model, the unit used for cost parameters is €/quantity of materials at the end of each time period. Table 6.6 presents the cost parameters and their proposed values.

Table 6.6: Cost parameters

Parameter	**Symbol**	**Material clusters**	**Point Estimates (€ per tonnes)**	**Reference**
Cost of buying materials from outsourcing facilities	$\dot{C}_{it}^{ok}$	sand and soil	7.42	[9]
		concrete	43.62	
		bricks	147.72	
		stones	37.23	
		ceramics	750.44	
		glass	44	
		gypsum	386.60	
		steel and iron	1054.24	
		copper	5750.50	
		other metals	1966.78	
		wood	1437	
		paper	100	
		plastics	1100	
		bitumen	250	
		isolation material	6695.85	
Operational cost within the same time period	$\dot{C}_{it}^{hk}$	(different for all materials)	$\dot{C}_{it}^{ok}/6$	
Storage cost within two consecutive periods	$\dot{C}_{i(t\rightarrow t+1)}^{hk}$	(different for all materials)	$\dot{C}_{it}^{hk}$ *2	
Revenues (selling materials in remanufacturers)	$\dot{P}_{it}^{mk}$	(different for all materials)	$\dot{C}_{it}^{ok}/2$	
Revenues (selling materials in recyclers)	$\dot{P}_{it}^{rk}$	(different for all materials)	$\dot{C}_{it}^{ok}/3$	
Cost of taxes to dispose the returned materials with no further utility in landfills	$\dot{C}_{it}^{lk}$	(same for all materials)	13	[8]
Transportation costs of returned materials (through the hub)	T_{ijt}	(same for all materials)	3	[14, 48]
Transportation costs of materials from outsourcing facilities	T_{oct}	(same for all materials)	T_{ijt} *2	

Comments:

In the MRA research [9], exploration about determining the price that secondary materials can be sold was conducted, by posing questions to relevant specialists and investigating the market prices. The result of this research was that information was not accurate and limited. In this research, the revenues from remanufacturing and recycling facilities are the price of newly manufactured materials divided by two and three respectively.

The operational cost is estimated as one-sixth of the price of purchasing new materials, while it is assumed that the storage cost is two times higher than the operational cost as an approximation of the time period the materials are held in the hub.

Another simplification is that same transportation cost is estimated for all material clusters, even though different vehicle could be assigned for each type and each quality grade of materials.

The hub, demolished and new projects are located within the municipality region, while the outsourcing facilities might be outside the municipality borders. To reflect these distance differences in the transportation cost and given the fact that location of facilities is not integrated into the model, the transportation cost from the outsourcing facilities is two times higher than the transportation cost of returned materials.

All the cost components are based on current prices, but the model entails prices in the future. Based on the Trading Economics global macro models and analysts expectations, the average inflation rate in 2019 and 2020 is approximated at 1.6 and 2 by the end of 2019 and 2020 respectively [10]. For this research, inflation rate of 1.8 is considered for all cost components in each time interval.

6.3. CO_2 parameters

In the model, the unit used for CO_2 emissions is CO_2 emissions /quantity of materials at the end of each time period. The CO_2 environmental impact factor is derived by the Dutch National Environmental database in which the quantity of each material produced, treated or transported is associated to carbon dioxide emissions (CO_2) [30]. Table 6.7 presents the CO_2 emissions and their proposed values.

Table 6.7: CO_2 parameters

Parameter	**Symbol**	**Material clusters**	**Point Estimates (€ per tonnes)**	**Reference**
CO_2 emissions of materials production in outsourcing facilities	CO_i^{ok}	sand and soil	0.00001208	[9]
		concrete	0.00009506	
		bricks	0.00024382	
		stones	0.00081061	
		ceramics	0.00200360	
		glass	0.00121606	
		gypsum	0.00041371	
		steel and iron	0.00174843	
		copper	0.00414818	
		other metals	0.01081722	
		wood	0.00015471	
		paper	0.00082260	
		plastics	0.00046990	
		bitumen	0.00112638	
		isolation material	0.00140133	
CO_2 emissions for operation activities in hub within the same time period	CO_i^{hk}	(same for all materials)	0.000772	[48]
CO_2 emissions for storing returned materials in hub within two consecutive periods	$CO_{g_1}^{hk}$	(same for all materials)	$CO_i^{hk}*2$	

CO_2 emissions of returned materials in new construction projects	CO_i^{ck}	(same for all materials)	0	[30]
CO_2 emissions of returned materials in remanufacturer	CO_i^{mk}	(same for all materials)	0	[30]
CO_2 emissions of returned materials in recycler	CO_i^{rk}	(same for all materials)	0	[30]
CO_2 emissions of returned materials in landfilling facility	CO_i^{lk}	sand and soil	0.0000078	[30]
		concrete	0.0000078	
		bricks	0.0000078	
		stones	0.0000078	
		ceramics	0.0000078	
		glass	0.0000078	
		gypsum	0.0000147	
		steel and iron	0.0000078	
		copper	0.0000147	
		other metals	0.0000078	
		wood	0.0000645	
		paper	0.0000078	
		plastics	0.0000689	
		bitumen	0.0001183	
		isolation material	0.0001227	
CO_2 emissions in transportation of returned materials between different nodes	CO_{ij}	(same for all materials)	0.0002132	[30]
CO_2 emissions in transportation of materials bought from outsourcing facilities	CO_{oc}	(same for all materials)	CO_{ij}*2	

7

Computational evaluation

The main purpose of this chapter is the evaluation of model results to investigate whether the material hub can firstly lead to economical and eventually to circular objectives under variations in the model inputs. Particularly, the solution steps described in Section 4.3 are implemented, whereas the main observations are entailed at the end of each section. The material streams are commented concerning their performance, while the key findings are summarized in the final section.

7.1. First solution step

7.1.1. Current situation results

In this section, the actual condition of no hub is approached in the Haarlem municipality. Following a discussion with experts, the returned materials after demolition are dispersed in various warehouses within the municipality without a plan for their final destination and their storage time [57]. So, it can be deduced that, currently, there is no standardized way in waste management techniques followed by the municipality. For this reason, a conservative scenario is considered to approach the current waste management practice. The current situation is simulated as if the waste after demolition ends up in landfills and the demand for all materials in new projects is covered by outsourcing facilities. The whole cost is calculated by multiplying the materials needed in all time periods with the price of newly manufactured materials and their transportation costs. In the current situation, there is also the cost involved in the demolition sites [either fixed costs (associated with hiring personnel and renting equipment) or variable costs (associated with the quantity of materials released)], but since it incurs independently of decision about the hub investment or not, this cost is omitted from the calculation. The scenario of no hub is chosen as the benchmark to evaluate the model results to draw conclusions about the hub performance as Construction and Demolition Waste (CDW) strategy.

7.1.2. Model results

The model results represent the cost involved in case of hub. In other words, this section will indicate the cost that the municipality undertakes to give a new purpose to returned materials by storing them temporarily in the hub facility. The model results constitute the candidate solutions which are investigated under the eleven scenarios of aggregate supply-demand ratio assuming uniform distributions (explained in Section 6.1.1). Once the minimum cost incurred in each scenario is found in the model, the fixed cost of opening a hub is added, which is approximated as €180.000 [48].

7.1.3. Comparison

The model results are evaluated in comparison with the current situation results given their economic performance. Requirements about the successful material hubs are that the returned products treatment should not be more expensive than the natural resources, so the market of secondary materials could be competitive compared to the production of the raw materials [56]. Specifically for this assessment, a question is posed to Haarlem municipality experts about the minimum profit they aim in business models including a hub to achieve also circular objectives. The neutral profit situation is desired by Haarlem municipality, meaning that investment of building a hub should not lead to any financial loss for the municipality.

7.1.4. Conclusions

Figure 7.1 illustrates that scenarios S5, S7, S9 and S10 can be candidate solutions, meaning that in those scenarios, the municipality can achieve cost savings by avoiding purchasing a part of materials required in new construction projects from outsourcing nodes, while in remaining scenarios, investing in a hub is not a financially viable solution for the municipality. In scenarios S1, S8 and S11, results are close by the neutral profit line either inducing financial loss or cost savings for the municipality, so those scenarios will be examined further.

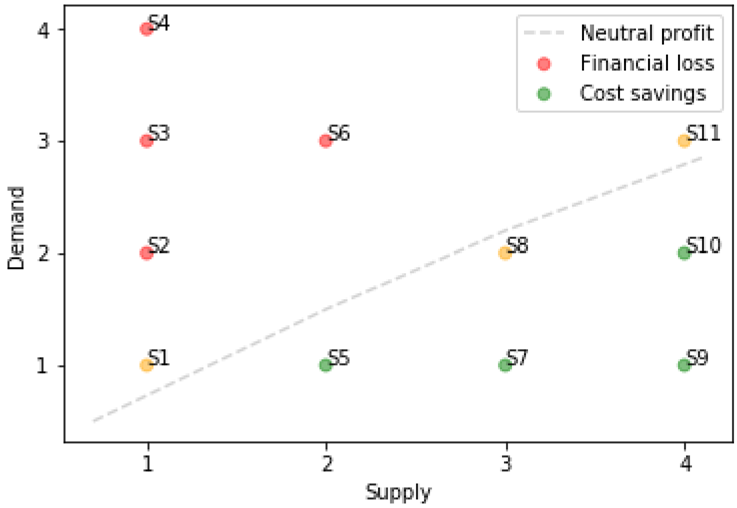


Figure 7.1: Candidate solutions after first solution step

From the results, it is observed that in scenarios in which demand is higher than supply, materials are not stored in the hub but directly transferred to their final destination. Subsequently, the material hub can be used only as a facility in which materials are collected in the hub at the beginning of time period, inspected, categorised and transferred in demand nodes till the end of the same time period.

It should be commented that because of the quality ranges assigned in each returned material after the demolition, the final rate of returned materials which can be reused in new projects is lower than the initial supply rate of materials. Assessment of the model results is carried out by not considering the quality ranges in contrast with the use of quality ranges as model inputs. In the ideal case that all materials can be directly reused in new projects, it is noticed that all scenarios are leading to cost savings, but the material hub is used only as a temporary passage of materials, not as storage within two consecutive times. Particularly, in S1, the demand for new materials is covered only by returned materials. In S2, S3, S4 and S6, the demand for materials is covered by both returned materials and materials from outsourcing facilities, which is less costly than demand covered only by outsourced materials. In S5, S7, S9 and S10, all returned materials can cover the demand and the remaining returned materials are sold to remanufacturers, since storage is more expensive option and the demand in the next time period can be covered by supply in the next time period. Because of the revenues of selling returned materials in remanufacturers, there is a profit achieved in that case. In S8 and S11, all returned materials can cover the demand and the remaining returned materials are sold to remanufacturers, but only cost savings can be effectuated. Taking all into consideration, it can be derived that the quality ranges assigned in each returned material after the demolition are the most critical inputs for the final result.

7.2. Second solution step

7.2.1. Model results

Table 7.1: Calibrations

Calibrations	Supply	Demand
a	±10%	±10%
b	±20%	±20%
c	±20%	±10%
d	±10%	±20%

Given the economic performance, the candidate solutions (S1, S5, S7, S8, S9, S10 and S11) are further appraised on the sixteen sets of instances described in Section 6.1.1 in which supply-demand dynamics differentiate within the time horizon. Because of the uncertainty level and the random generation of the sets of instances, the supply and demand for returned materials in each time period are perturbed in different ways. Two possible variations (±10% and ±20%) of those parameters are created which lead to four combinations of supply-demand calibrations. So, in each set of instances, we perturb the supply-demand in the following calibrations (a, b, c and d), as depicted in Table 7.1.

Because the parameter values are randomly selected from those calibration intervals, 100 model runs are conducted per set of instances. The optimal cost range in each set of instances is determined by finding the interval of average values of optimal cost with 95% confidence level and compared with the actual situation for all scenarios.

7.2.2. Comparison

S1

Following the comparison between the model results and the actual situation within scenario S1, it is concluded that in all sets of instances, only financial loss can be achieved while only material 1 (sand and soil) is stored within two consecutive times. In particular, the hub is mainly used as a temporary passage of materials in which only categorisation of materials can occur. Subsequently, this scenario is not tested further in the following steps.

S5

Regarding the sets of instances 1_1, 2_2, 3_3 and 4_4, it is concluded that even though there are cost savings for the municipality, the supply and demand quantities follow identical patterns and storage of materials within two consecutive time periods does not exist.

In the remaining sets of instances, in the time periods in which supply-demand quantities are approaching each other, storage of materials takes place aside from the cost savings for the municipality. Another remark of the analysis is that mainly material 1 (sand and soil) and material 13 (plastics) are stored, which is resulted from the high reusability percentage (80% and 50% respectively) estimated by experts judgment (as shown in Section 6.1.2). The relation between the cost induced in the current situation and the proposal of the hub in all settings is recorded in Table 7.2. The minimum relation is calculated by dividing the cost in the current situation by the maximum cost incurred in the hub case in each pattern (a, b, c, d), whereas the maximum relation is calculated by dividing the cost in the current situation by the minimum cost incurred in the hub case in each pattern (a, b, c, d). The maximum and the minimum cost in the hub case are acquired by the confidence interval found from the 100 model runs. It is noticed that in scenario S5, the minimum and maximum relation of economic performance between the current situation and the hub case is estimated as 1.025 and 1.033 respectively, meaning that the cost savings could vary between 2.5% and 3.3%.

The relation between the maximum storage of materials and the average demand for materials in all time periods is investigated. In Table 7.3, the percentage of maximum storage of materials on the average demand in each set of instances is recorded, while the relation of those percentages with each other is illustrated in Figure 7.2. It should be remarked that a small percentage of materials needed in new projects are covered by the materials which are stored in the hub within two consecutive time periods. The maximum percentage is 1.856% which is recorded in the set of instances 1_4. The set of instances with at least 1% storage rate (1_2, 1_3, 1_4, 2_1, 3_1, 4_2) constitute the candidate solutions and will be tested further in the third solution step.

Table 7.2: Relation of economic performance between current situation and the model results in scenario S5

Sets of instances	Min Relation	Max Relation
S5 (1_2)	1.025	1.033
S5 (1_3)	1.027	1.035
S5 (1_4)	1.017	1.030
S5 (2_1)	1.032	1.043
S5 (2_3)	1.025	1.033
S5 (2_4)	1.020	1.026
S5 (3_1)	1.032	1.040
S5 (3_2)	1.020	1.031
S5 (3_4)	1.018	1.027
S5 (4_1)	1.033	1.044
S5 (4_2)	1.026	1.035
S5 (4_3)	1.024	1.033

Table 7.3: Maximum storage/ Average demand for materials in all time periods in scenario S5

Sets of instances	Maximum storage/ average demand in all time periods (%)
S5 (1_2)	1.232
S5 (1_3)	1.308
S5 (1_4)	1.856
S5 (2_1)	1.843
S5 (2_3)	0.238
S5 (2_4)	0.933
S5 (3_1)	1.829
S5 (3_2)	0.613
S5 (3_4)	0.847
S5 (4_1)	0.444
S5 (4_2)	1.816
S5 (4_3)	0.739

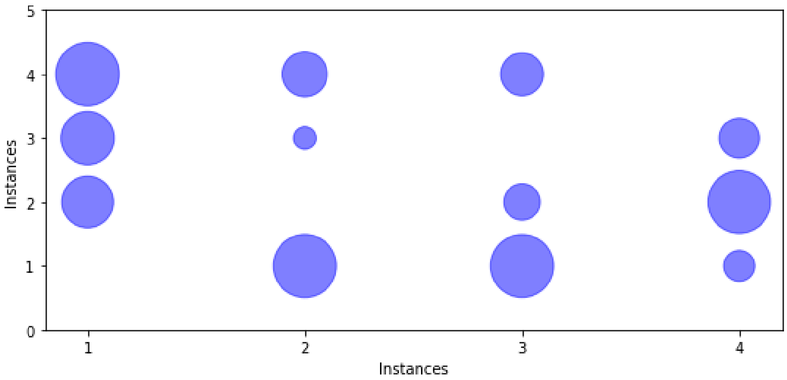


Figure 7.2: Maximum storage/ Average demand for materials in all time periods in scenario S5

S7

It should be mentioned that there are cost savings in all sets of instances, while the storage of materials takes place within two consecutive time periods. It is observed that material 13 (plastics) is stored in all sets of instances, whereas materials 1 (sand and soil), 8 (steel and iron) and 14 (bitumen) are also stored in certain settings.

The relation between the cost occured in the current situation and the proposal of the hub in all settings is calculated in the same way as indicated in scenario S5 and recorded in Table 7.4. It is noticed that in scenario

S7, the minimum and maximum relation of economic performance between the current situation and the hub case is computed as 1.108 and 1.120 respectively, meaning that the cost savings could range between 10.8% and 12%.

Table 7.4: Relation of economic performance between current situation and the model results in scenario S7

Sets of instances	Min Relation	Max Relation
S7 (1_1)	1.118	1.130
S7 (1_2)	1.106	1.118
S7 (1_3)	1.107	1.118
S7 (1_4)	1.102	1.114
S7 (2_1)	1.118	1.132
S7 (2_2)	1.106	1.117
S7 (2_3)	1.110	1.119
S7 (2_4)	1.100	1.111
S7 (3_1)	1.116	1.126
S7 (3_2)	1.107	1.117
S7 (3_3)	1.101	1.118
S7 (3_4)	1.099	1.111
S7 (4_1)	1.118	1.132
S7 (4_2)	1.106	1.118
S7 (4_3)	1.108	1.120
S7 (4_4)	1.101	1.114

The relation between the maximum storage of materials and the average demand for materials in all time periods is recorded in Table 7.5. Taking all into account, it should be mentioned that a small percentage of materials required in new projects are covered by the materials which are stored in the hub within two consecutive time periods. The maximum percentage is 2.328% which appears in the set of instances 3_1. The relation of those percentages with each other is exhibited in Figure 7.3. The set of instances with at least 1% storage rate (1_3, 3_1, 4_2) are deemed as the candidate solutions and will be examined further in the third solution step.

Table 7.5: Maximum storage/ Average demand for materials in all time periods in scenario S7

Sets of instances	Maximum storage/ average demand in all time periods (%)
S7 (1_1)	0.017
S7 (1_2)	0.037
S7 (1_3)	1.392
S7 (1_4)	0.013
S7 (2_1)	0.010
S7 (2_2)	0.002
S7 (2_3)	0.045
S7 (2_4)	0.690
S7 (3_1)	2.328
S7 (3_2)	0.006
S7 (3_3)	0.018
S7 (3_4)	0.026
S7 (4_1)	0.017
S7 (4_2)	1.910
S7 (4_3)	0.011
S7 (4_4)	0.015

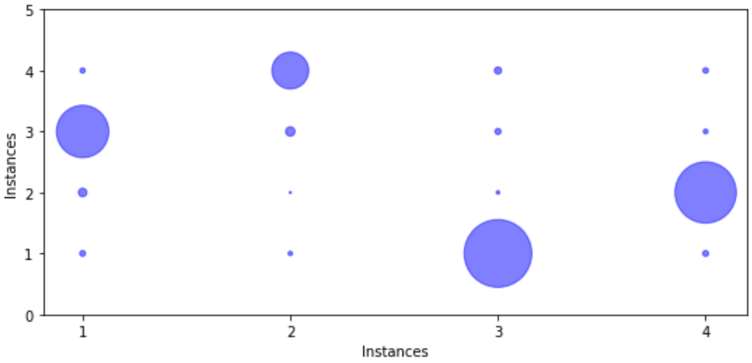


Figure 7.3: Maximum storage/ Average demand for materials in all time periods in scenario S7

S8

The comparison between the model results and the actual situation within scenario S8 leads to financial loss in all sets of instances. So, the analysis of this scenario will not continue in the following steps.

S9

In all sets of instances there are cost savings for the municipality and storage of materials within two consecutive time periods occurs. It is worth mentioning that material 1 (sand and soil), material 8 (steel and iron), material 13 (plastics) and material 14 (bitumen) are mostly stored, which is resulted from the high reusability percentage (80% , 20%, 50 and 20% respectively) derived by experts judgment.

The relation between the cost occured in the current situation and the model results in all settings is similarly computed as in the previous scenarios and recorded in Table 7.6. It is noticed that in scenario S9, the minimum and maximum relation of economic performance between the current situation and the hub case is estimated as 1.201 and 1.216 respectively, meaning that cost savings between 20.1% and 21.6% can be reached.

Table 7.6: Relation of economic performance between current situation and the model results in scenario S9

Sets of instances	**Min Relation**	**Max Relation**
S9 (1_1)	1.215	1.227
S9 (1_2)	1.199	1.215
S9 (1_3)	1.200	1.215
S9 (1_4)	1.195	1.206
S9 (2_1)	1.209	1.226
S9 (2_2)	1.200	1.214
S9 (2_3)	1.202	1.216
S9 (2_4)	1.191	1.207
S9 (3_1)	1.211	1.224
S9 (3_2)	1.200	1.214
S9 (3_3)	1.203	1.222
S9 (3_4)	1.193	1.210
S9 (4_1)	1.214	1.226
S9 (4_2)	1.199	1.216
S9 (4_3)	1.204	1.219
S9 (4_4)	1.189	1.208

The relation between the maximum storage of materials and the average demand for materials in all time periods is investigated. In Table 7.7, the percentage of maximum storage of materials on the average demand in each set of instances is catalogued. It should be remarked that a small percentage of materials needed in new projects are covered by the materials which are stored in the hub within two consecutive time periods and particularly the maximum percentage is 0.177% which is recorded in the set of instances 1_2. The storage rate of materials is regarded as low, so those potential solutions will be no further tested in the following solution steps.

Table 7.7: Maximum storage/ Average demand for materials in all time periods in scenario S9

Sets of instances	Maximum storage/ average demand in all time periods (%)
S9 (1_1)	0.024
S9 (1_2)	0.177
S9 (1_3)	0.036
S9 (1_4)	0.028
S9 (2_1)	0.007
S9 (2_2)	0.036
S9 (2_3)	0.022
S9 (2_4)	0.048
S9 (3_1)	0.039
S9 (3_2)	0.088
S9 (3_3)	0.025
S9 (3_4)	0.072
S9 (4_1)	0.061
S9 (4_2)	0.014
S9 (4_3)	0.013
S9 (4_4)	0.011

S10

Regarding the sets of instances 1_1, 2_2, 3_3 and 4_4, it is concluded that even though there are cost savings for the municipality, storage of materials within two consecutive time periods does not take place, so those sets of instances will be no further examined.

In the remaining sets of instances, the storage of materials occurs in addition with the cost savings for the municipality, but mainly for materials 1 (sand and soil) and 13 (plastics). The relation between the cost induced in the current situation and the proposal of the hub in all sets of instances is calculated as in the previous sections. From Table 7.8 which entails the aforementioned relation for scenario S10, it is detected that the minimum and maximum relation of economic performance between the current situation and the hub case is estimated as 1.027 and 1.036 respectively, meaning that the cost savings could range between 2.7% and 3.6%.

Table 7.8: Relation of economic performance between current situation and the the model results in scenario S10

Sets of instances	Min Relation	Max Relation
S10 (1_2)	1.027	1.034
S10 (1_3)	1.028	1.036
S10 (1_4)	1.021	1.029
S10 (2_1)	1.032	1.041
S10 (2_3)	1.026	1.036
S10 (2_4)	1.020	1.029
S10 (3_1)	1.035	1.043
S10 (3_2)	1.025	1.033
S10 (3_4)	1.019	1.029
S10 (4_1)	1.037	1.046
S10 (4_2)	1.027	1.034
S10 (4_3)	1.029	1.038

The percentage of the maximum storage of materials on the average demand for materials in all time periods is recorded in Table 7.9, whereas Figure 7.4 pictures the relation of those percentages with each other. To conclude, a small percentage of materials needed in new projects are covered by the materials which are stored in the hub within two consecutive time periods. The maximum percentage is 2.311% which is recorded in the set of instances 3_1. The set of instances with at least 1% storage rate (1_3, 2_1, 2_4, 3_1, 3_4, 4_2, 4_3) constitute the candidate solutions and will be tested further in the third solution step.

Table 7.9: Maximum storage/ Average demand for materials in all time periods in scenario S10

Sets of instances	Maximum storage/ average demand in all time periods (%)
S10 (1_2)	0.493
S10 (1_3)	1.791
S10 (1_4)	0.723
S10 (2_1)	1.098
S10 (2_3)	0.731
S10 (2_4)	1.145
S10 (3_1)	2.311
S10 (3_2)	0.339
S10 (3_4)	1.015
S10 (4_1)	0.101
S10 (4_2)	1.876
S10 (4_3)	1.708

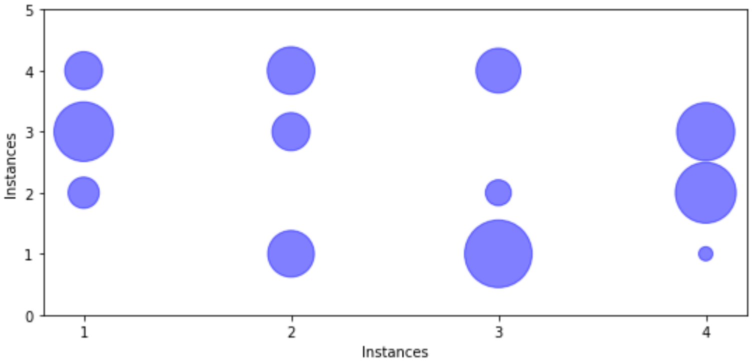


Figure 7.4: Maximum storage/ Average demand for materials in all time periods in scenario S10

S11

The comparison between the model results and the actual situation within scenario S11 presents that there is financial loss in all sets of instances, leading to no further evaluation of this scenario.

7.2.3. Conclusions

This evaluation step is performed to strengthen the liability of the model results, since the model inputs of supply-demand fluctuations are generated randomly. To sum up, it is financially viable to build a hub in scenarios of supply-demand ratio S5, S7 and S10 under random distributions. Those candidate solutions are derived from investigating whether there are cost savings for the municipality and storage of materials within two consecutive time periods.

The relation between the cost occurred in case of no hub and the model results is calculated in each scenario. By comparing the relations of each scenario, it is concluded that the highest rate of cost savings is detected in scenario S7 (3:1) (range 10.8-12%), while in S5 (2:1) and S10 (4:2) the cost savings fluctuate between 2.5-3.3% and 2.7-3.6% respectively. All things considered, if the supply is three times more than the demand, the cost savings can be increased 3.3-4% in comparison with the scenario in which supply is two times more than the demand rate.

Another finding in this evaluation step is the percentage of maximum storage on the average demand for returned materials in all time periods for each scenario. In scenario S7, this rate is 2.328% in comparison with scenarios S5 and S10 in which this rate is 1.856 and 2.311% respectively.

7.3. Third solution step

All the candidate solutions derived by the previous step are evaluated beyond by undertaking a sensitivity analysis in the remaining parameters (capacity and cost components). By recording the differences in the cost objective function, the influence of those variations in the final cost is appraised and investigation of the critical parameters is conducted concerning the economic performance of the model. If the differences in the optimal cost are within a level which will not induce financial loss for the municipality, the parameters are not critical. Otherwise, they are characterised as critical and attention should be given to their selection.

7.3.1. Model results

Capacity

The maximum capacity was considered until this point of analysis, meaning that the capacity constraint was relaxed and did not play an important role in the final result of cost. The gradual decrease of capacity level is implemented. The maximum capacity level is estimated as the maximum supply of materials in one time period and this level is gradually reduced per 10% till half of the maximum storage capacity to explore the difference in results.

In the candidate solutions in all scenarios, it is observed that once the maximum storage capacity is reduced, the maximum storage percentage is increased, meaning that more materials are stored in each time period. Decrease of the capacity level induced a divergence in the final cost in comparison with the optimal cost with maximum storage capacity. The range of this differentiation is -1.072% and 2.406% in scenario S5, -1.928% and 1.763% in scenario S7, -1.765% and 1.963% in scenario S10. From this analysis, it can be stated that this difference is not substantial, so the storage capacity level is not a critical parameter in the decision-making for building a hub or not. In the following steps, the constraints about the capacity level will be neglected.

Cost parameters

For all the cost parameters, a point estimate was used until this analysis step, but in this section, sensitivity analysis is conducted by changing the relations of the cost components. In this way, we examine how vulnerable is the model in the fluctuation of future values in the market. Cost relations which are not favorable in comparison with the base case are defined, as shown in Table 7.10.

Table 7.10: Cost components relations

Cost components	**Current situation**	**No favorable situation**
Cost of buying materials from outsourcing facilities	$\dot{C}_{it}^{ok}$	$\dot{C}_{it}^{ok}$
Operational cost within the same time period	$\dot{C}_{it}^{ok}/6$	$\dot{C}_{it}^{ok}/4$
Storage cost within two consecutive periods	$\dot{C}_{it}^{ok}/3$	$\dot{C}_{it}^{ok}/2$
Revenues (selling materials in remanufacturers)	$\dot{C}_{it}^{ok}/2$	$\dot{C}_{it}^{ok}/2.5$
Revenues (selling materials in recyclers)	$\dot{C}_{it}^{ok}/3$	$\dot{C}_{it}^{ok}/3.5$
Transportation costs of returned materials (through the hub)	T_{ijt}	T_{ijt}
Transportation costs of materials from outsourcing facilities	T_{ijt} *2	T_{ijt} *2.5

In a preliminary analysis, it was deduced that after altering all the cost relations simultaneously, the optimal cost was increased in such a level which is leading to financial loss for the municipality. For this reason, the cost parameters were grouped into three categories: a) operational and storage costs, b) revenues by recyclers and remanufacturers, c)transportation costs and we examine the influence of each cost category in the objective value of cost.

S5

Modification of the cost components in the first category leads to a sizeable increase in the final cost at such a level which effectuates financial loss for the municipality. The breaking point of the cost components of this category is explored and depicted in Figure 7.5.

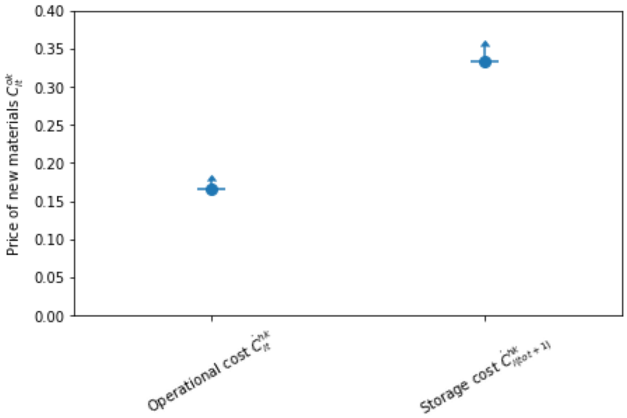


Figure 7.5: Breaking point of the cost components in scenario S5

By varying the second category of costs, it is observed that the relation between the cost incurred in the no hub situation and the model results slightly decreases in comparison with the base case. In other words, the optimal cost rises, but the influence is not meaningful to lead to financial loss for the municipality. Those relations are recorded in Table 7.11, showing that the cost savings could range between 1% and 2.9%.

Table 7.11: Relation of economic performance after changing cost components in the second category in scenario S5

Sets of instances	Min relation	Max relation
S5 (1_2)	1.016	1.019
S5 (1_3)	1.018	1.020
S5 (1_4)	1.010	1.013
S5 (2_1)	1.027	1.029
S5 (3_1)	1.024	1.026
S5 (4_2)	1.017	1.020

Table 7.12 reports the relationship between the final cost in no hub and hub situation in case of change in the transportation costs. The conclusion is that this relation barely decreases in comparison with the base case, since the cost savings could fluctuate between 1% and 2.7%. To sum up, variation in transportation costs continues inducing cost savings, meaning that this parameter does not affect considerably the end result.

Table 7.12: Relation of economic performance after changing cost components in the third category in scenario S5

Sets of instances	Min relation	Max relationn
S5 (1_2)	1.016	1.018
S5 (1_3)	1.018	1.020
S5 (1_4)	1.010	1.013
S5 (2_1)	1.025	1.027
S5 (3_1)	1.024	1.026
S5 (4_2)	1.017	1.019

S7

Altering the costs in the first and second category separately leads to important rises in the objective value of cost in such a level which result in financial loss for the municipality. The breaking point of the cost components of the first and second categories is estimated and illustrated in Figure 7.6.

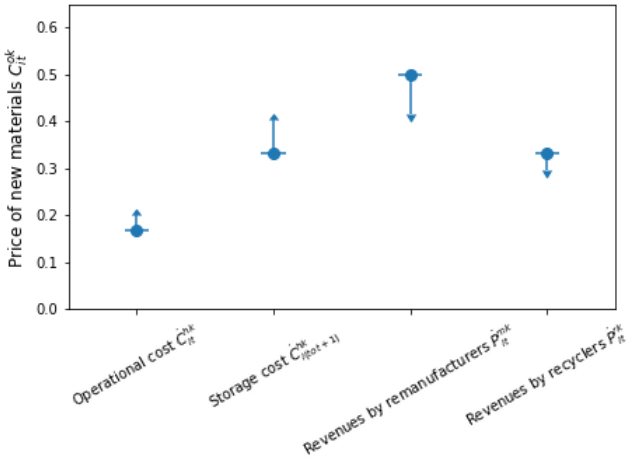


Figure 7.6: Breaking point of the cost components in scenario S7

In case of a change in the third cost category, it is found that the transportation costs do not influence significantly the financial result. The relation between the final cost in case of no hub and hub is recorded in Table 7.13. Despite the fact that this relation declines in comparison with the base case (range between 9.8% and 10.9%), the result is favorable for the municipality since there are cost savings.

Table 7.13: Relation of economic performance after changing cost components in the third category in scenario S7

Sets of instances	**Min relation**	**Max relationn**
S7 (1_3)	1.097	1.101
S7 (3_1)	1.104	1.109
S7 (4_2)	1.098	1.102

S10

Similarly, it is discovered that the variations in the cost components in first and second category separately could cause notable increase in the objective value of cost resulting financial loss for the municipality. The points of the cost components for which cost savings can be induced are presented in Figure 7.7.

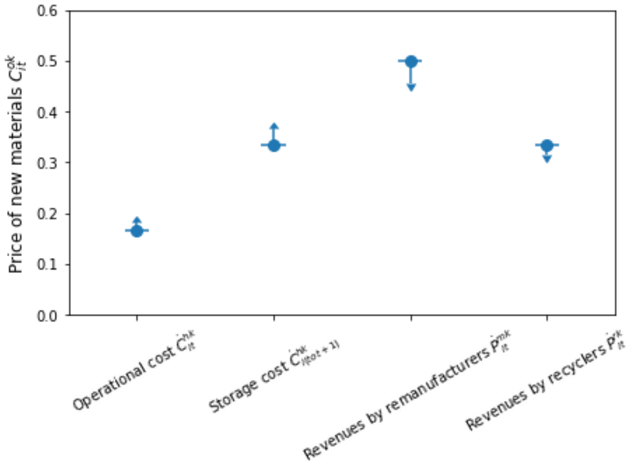


Figure 7.7: Breaking point of the cost components in scenario S10

In case of change in the third cost category, the transportation costs barely influence the eventual financial result. The relation between the final cost in case of no hub and hub is recorded in Table 7.14. This relation decreases in comparison with the base case (range between 1% and 2.7%), but the impact is negligible since there are cost savings for the municipality.

Table 7.14: Relation of economic performance after changing cost components in the third category in scenario S10

Sets of instances	Min relation	Max relationn
S10 (1_3)	1.018	1.020
S10 (2_1)	1.024	1.027
S10 (2_4)	1.010	1.012
S10 (3_1)	1.024	1.026
S10 (3_4)	1.010	1.012
S10 (4_2)	1.017	1.020
S10 (4_3)	1.019	1.022

7.3.2. Conclusions

From this analysis step, the main conclusion that can be drawn is that the capacity of the hub and the transportation costs do not play a crucial role in economic performance of the model, whereas the operational costs, storage costs and revenues by remanufacturers and recyclers are deemed as critical factors for the objective value of cost. Table 7.15 summarizes the range of critical parameters in which there are cost savings for the municipality in each scenario. This span is in function of the price of newly manufactured materials.

Table 7.15: Critical parameters

Scenarios	Critical parameters
S5	Operational cost(1/6-1/5.6) Storage cost(1/3-2/5.6)
S7	Operational cost(1/6-1/5-5.1) Storage cost(1/3-2/5-5.1) Revenues by remanufacturers(1/2-1/2.4) Revenues by recyclers(1/3-1/3.4)
S10	Operational cost(1/6-1/5.5) Storage cost(1/3-2/5.5) Revenues by remanufacturers(1/2-1/2.2) Revenues by recyclers(1/3-1/3.2)

For further explanation of the table above, an example is provided. In scenario S5, in which the supply-demand ratio is 2:1, it is financially viable to invest in a hub if the relative numbers of new materials price/ operation cost and new materials price/ storage cost are 1/6-1/5.6 and 1/3-2/5.6 respectively.

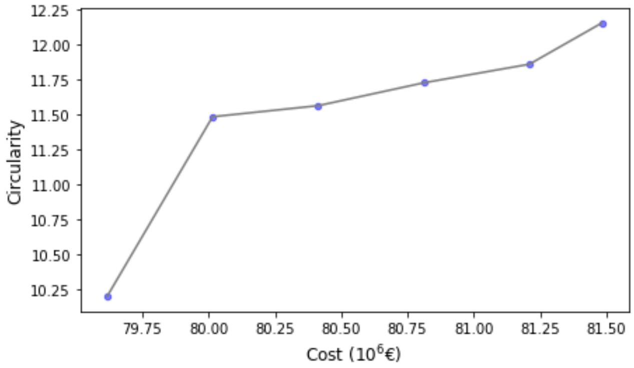
7.4. Fourth solution step

All the optimal solutions for the previous steps are regarded as candidate solutions for the final decision. In this section, the evaluation of the candidate solutions regarding their circular performance (circularity rate and $C0_2$ emissions) is conducted. One set of instances is investigated per scenario [S5 (1_4), S7 (3_1), S10 (3_1)], which is selected based on the maximum storage percentage found in the second evaluation step. To find the solution in this multi-objective problem with contradicting objectives, the ε-constraint method is implemented, as explained in Appendix B. In this method, one objective function is optimised embedding the remaining objective functions as additional constraints in the model presented in Chapter 5.

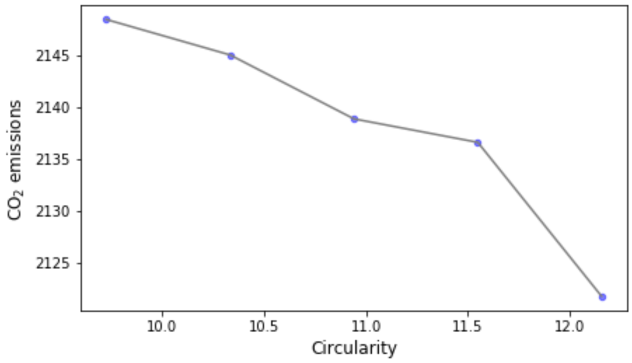
Specifically, the three objectives are prioritized based on their importance as follows: minimization of cost, maximization of circularity and minimization of $C0_2$ emissions. Keeping the cost in a low rate to effectuate either neutral profit or cost savings situation is selected as the objective of primary concern. Circularity is deemed as the second most important objective because of the municipality goals to embrace circularity in the current waste management practices. Since the optimal value for the minimum cost is identified in the second solution step, the optimal value of maximum circularity is investigated subjected to the constraint that the cost will not exceed more than a certain percentage (ε_1) the optimal minimum value. The same procedure follows in searching for the minimum $C0_2$ emissions without sacrificing more than certain percentages ($\varepsilon_1, \varepsilon_2$) the optimal value of minimum cost and maximum circularity. The cost boundaries (ε_1) are selected in such a way to induce neutral profit or cost savings situation for the municipality, whereas the circularity (ε_2) is bounded within the minimum and maximum optimal value derived from the second step of ε-constraint method. Multiple solutions of the three conflicting objectives, the Pareto solutions, are deduced by various combinations of ε_1 and ε_2. Efficient frontiers are formulated by plotting all the sets of Pareto optimal solutions. In particular, those curves visualise how the objective function of $C0_2$ emissions is differentiated by changing the optimal values of cost and circularity in each candidate scenario. The Pareto frontiers facilitate the decision-makers in the municipality to compare the three objectives of cost, circularity and $C0_2$ emissions and eventually determine the most favored solution among all the candidate scenarios.

7.4.1. Model results

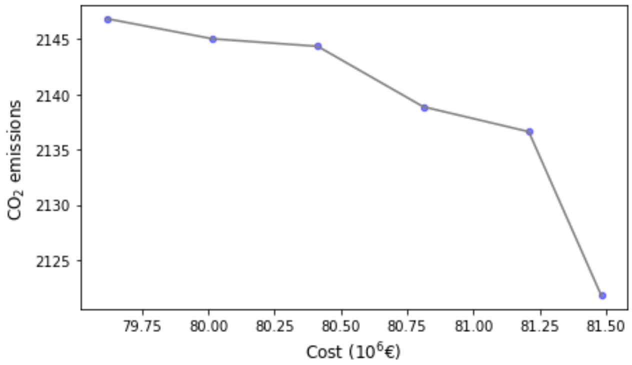
S5 (1_4)



(a) Cost-Circularity



(b) Circularity-$C0_2$ emissions



(c) Cost-$C0_2$ emissions

Figure 7.8: Optimal Pareto solutions in S5

In scenario S5, the boundaries (ε_1) of the optimal values of cost are between 1 and 1.023, while the circularity is bounded within the following span of its optimal value: $0.8 \leq \varepsilon_2 \leq 1$.

From Figure 7.8a, it is evident that once the minimum cost slightly rises (0.5%), the circularity rate sharply increases (12.63%). The initial surge is followed by a slower growth of circularity (5.85%), as the cost is gradually augmented (0.5-2.3%). Figure 7.8b illustrates that 25% rise of optimal circularity can lead to a slight decrease in the CO_2 emissions (1.24%), whereas there is an insignificant drop of CO_2 emissions (1.18%), as the minimum cost steadily rises (2.3%), as presented in Figure 7.8c.

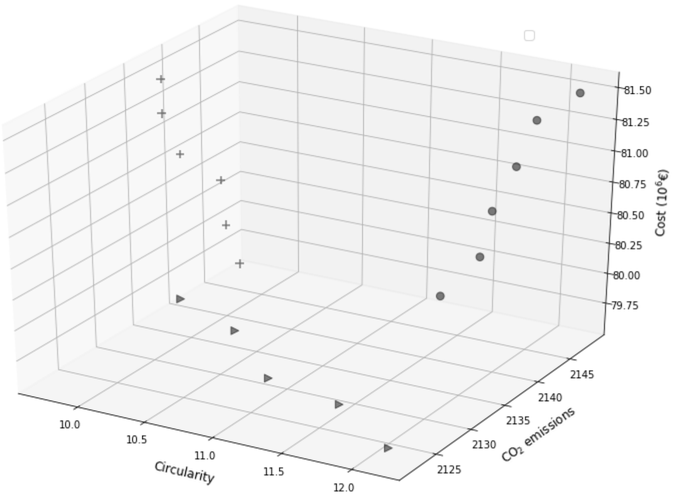


Figure 7.9: 3-D Pareto solutions in S5

This analysis leads to the following important remark. The minimum cost of investing to a material hub could rise up to 2.3% without leading to financial loss for the municipality, which induces up to 19.22% improvement of the circularity rate and up to 1.18% drop of CO_2 emissions.

S7 (3_1)

In scenario S7, the boundaries (ε_1) of the optimal values of cost are between 1 and 1.125, while the circularity is bounded within the following span of its optimal value: $0.8 \leq \varepsilon_2 \leq 1$.

The Figures (7.11a-7.11c) follow similar patterns with Figures (7.8a-7.8c) in scenario S5. Those Pareto frontiers indicate the fact that the minimum cost can be augmented up to 12.5% and still be within the acceptable rate to achieve cost savings for the municipality. This rise can result up to 3.09% increase in circularity rate and up to 1.48% drop of CO_2 emissions.

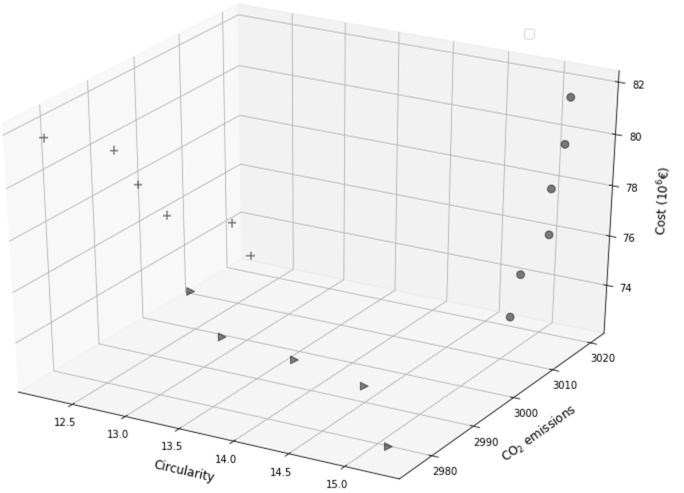
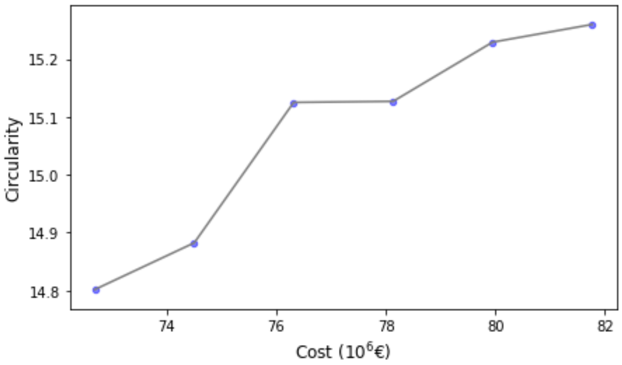
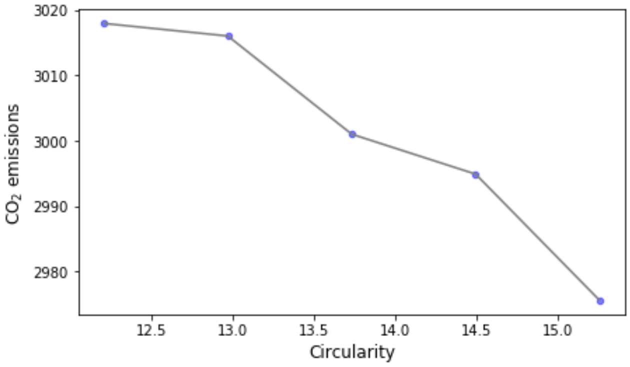


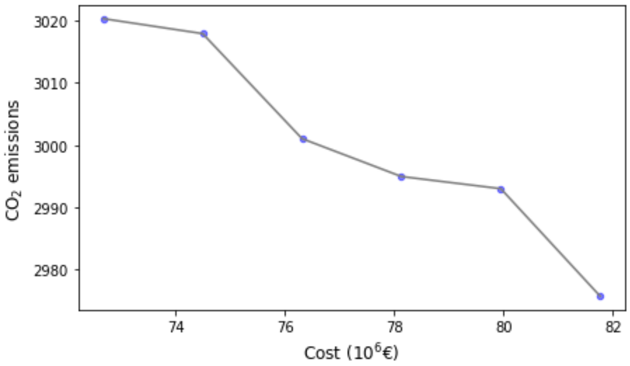
Figure 7.10: 3-D Pareto solutions in S7



(a) Cost-Circularity



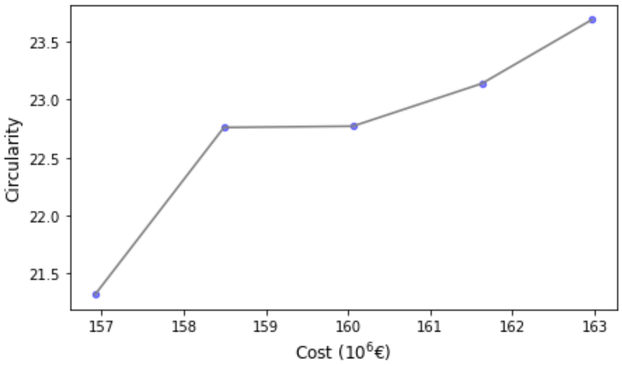
(b) Circularity-C0_2 emissions



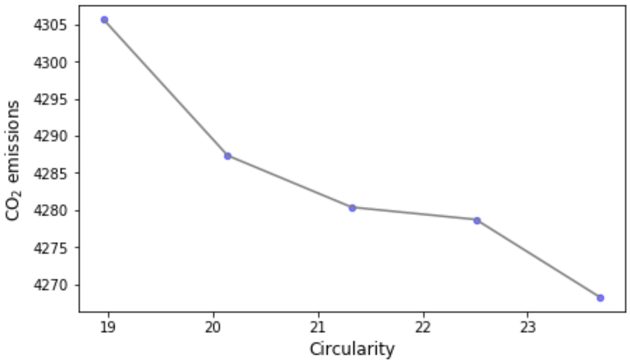
(c) Cost-C0_2 emissions

Figure 7.11: Optimal Pareto solutions in S7

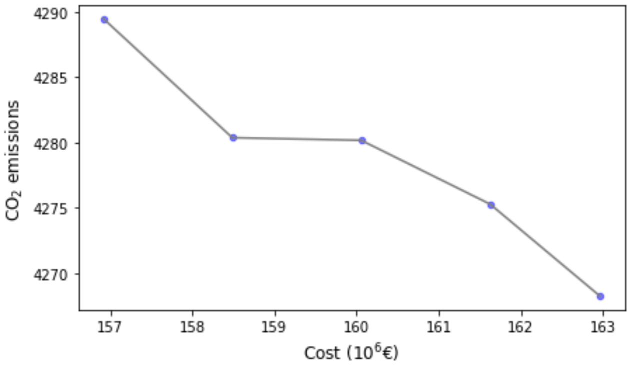
S10 (3_1)



(a) Cost-Circularity



(b) Circularity-C0$_2$ emissions



(c) Cost-C0$_2$ emissions

Figure 7.12: Optimal Pareto solutions in S10

In scenario S10, the boundaries (ε_1) of the optimal values of cost are between 1 and 1.039, while the circularity is bounded within the following span of its optimal value: $0.8 \leq \varepsilon_2 \leq 1$.

The final optimal solutions are presented in Figures 7.12a-7.12c which follow similar patterns with Figures 7.8a-7.8c in scenario S5. It is worth mentioning that 3.9% increase of the minimum cost could be financially viable for the municipality to invest in the hub, while the circularity level can increase up to 11.19% and CO_2 emissions can be reduced up to 0.87%.

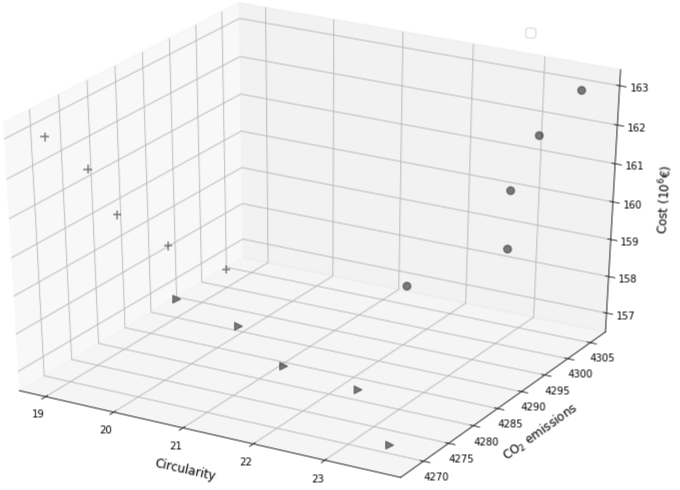


Figure 7.13: 3-D Pareto solutions in S10

7.4.2. Conclusions

So it can be concluded that once there is improvement regarding the circularity aspects, the situation is not favorable for the financial perspective. It depends on the decision-makers in the municipality to decide which optimal solution is satisfying.

The optimal final solutions in all scenarios are compared and relevant statements are formulated. By comparing scenarios S5 and S7, it would appear that by changing the supply/demand ratio from 2:1 to 3:1, the maximum circularity can be increased up to 25.51% while comparing scenarios S5 and S10 (change the supply/demand ratio from 2:1 to 4:2) the maximum circularity is doubled.

Comparison between scenarios S5 and S7 demonstrates that by changing the supply/demand ratio from 2:1 to 3:1, the minimum $C0_2$ emissions can be augmented up to 40.24%, while the minimum $C0_2$ emissions in scenario S10 can reach two times the value of minimum $C0_2$ emissions in scenario S5 (change the supply/demand ratio from 2:1 to 4:2).

7.5. Material streams

From the analysis in the first solution step, it was concluded that without the quality ranges assigned in each returned material after demolition, the model results induce cost savings for the municipality in all scenarios by reusing all the returned materials from the hub in new projects. However, this situation does not correspond to reality, due to uncertainty involved regarding the quality of returned materials after demolition. From the second evaluation step, it is discovered that only materials 1 (sand and soil), 8 (steel and iron), 13 (plastics) and 14 (bitumen) are stored within two consecutive times in the hub in various scenarios. It is worth mentioning that the expected percentage of those materials which can be reused after demolition is higher in relevance with the remaining materials, as indicated in Section 6.1.2. Taking those two findings into account, it can be deduced that the input of expected quality of materials after demolition is the most critical parameter for the model results and attention should be given to this approximation.

7.6. Key findings

In this chapter, the candidate solutions are extensively examined by varying the model inputs. The analysis begins with testing the model results regarding their economic performance under various scenarios of supply-demand ratio in the first solution step (Section 7.1) and fluctuations of the supply-demand dynamics within the predefined scenarios in the second solution step (Section 7.2). Their financial performance is inquired by exploring whether investing in the material hub could evoke cost savings for the municipality as waste management practice in comparison with the current situation. The second financial criterion for concluding to the optimal solutions is the storage percentage of materials within two consecutive periods in the hub. The results from the first evaluation step provide evidence that in scenarios in which supply is higher than demand (scenarios S5(2:1), S7(3:1), S9(4:1) and S10(4:2), the municipality can achieve cost savings by avoiding purchasing a part of new materials needed in new construction projects. Given the fact that fluctuation of supply-demand dynamics in each scenario was performed randomly, a sensitivity analysis was conducted for those model inputs. Subsequently, the study in the second step demonstrates that under the following supply-demand ratio of returned materials S5(2:1), S7(3:1) and S10(4:2), those two financial criteria can be fulfilled. This solution step appears the following cost savings percentages: 2.5-3.3% in scenario S5, 10.8-12% in scenario S7 and 2.7-3.6% in scenario S10. By associating the supply-demand ratio with the cost savings achieved in each scenario, it can be stated that if the supply is three times more than the demand, the cost savings can be increased 3.3-4% in comparison with the scenario in which supply is twice the demand rate.

In the third solution step (Section 7.3), the financial evaluation of the candidate solutions continues by altering the capacity of material hub and the relation between the cost components. This sensitivity analysis underlines that the operational cost, storage cost of returned materials in the hub and the revenues by selling returned materials in remanufacturers and recyclers are critical in the decision-making for the material hub investment and the acceptable range in which those parameters should be within are reported. Another outcome of this step is that the influence of capacity of the hub and the transportation costs is negligible for the economic performance of the model.

The fourth solution step (Section 7.4) entails the model output in relevance to the circular goals (circularity and CO_2 emissions). The problem is solved as a three-objective model by applying the ε-constraint method, in which one objective function is optimised integrating the remaining objectives as additional constraints. The optimal final solutions of the three objectives are found in all scenarios and the following conclusions are drawn. Improvement regarding the circular objectives can lead to deterioration of the financial aspect. Besides, it should be mentioned that the optimal objective values are not found simultaneously in one scenario, since the optimal circularity is effectuated in scenario S10, the minimum CO_2 emissions are resulted in scenario S5 and the most cost savings incur in scenario S7, as presented in Table 7.16. It depends on the decision-makers in the municipality to decide which optimal solution is more satisfying.

Table 7.16: Cost savings and circular objectives

Scenarios	**Cost savings (%)**	**Circularity**	**CO_2 emissions**
S5(2:1)	2.5-3	10.20-12.16	2121.78-2148.47
S7(3:1)	10.8-12	14.80-15.26	2975.62-3020.37
S10(4:2)	2.7-3.6	21.31-23.69	4268.26-4305.68

A final remark is that the forecasted percentage of returned materials which can be reused is deemed as the most determinant element in the model inputs and can radically influence the model results.

8

Conclusions

8.1. Scientific and practical contributions

8.1.1. Scientific contributions

As highlighted in the literature review, the financial and circular benefits of building a material hub are present in certain cases, while lacking in others. Various reasons incite this difference, such as the heterogeneity of returned materials in nature, volume and quality. This research contributes to the academia by proving that the statements in the literature comply with the research results. This derives from the fact that the critical parameters for a financially viable scenario are: the range of materials which are reused, the supply-demand ratio, the fluctuations of supply-demand within a time horizon, the prices in which returned materials are sold to recyclers/ remanufacturers and the demand for returned materials by those parties. This finding is in alignment with the argument found in the theory in which one possible reason for non financially attractive result is the complexity in determining the treatments of returned materials and their rate of potential revenues.

Another scientific contribution of this research is the integration of multiple concepts of Operation Research (OR) literature in one model. The four concepts explained in literature review (Section 2.3) are: environmental objectives, uncertainties in quality categorisation of returned materials, uncertainties in quantity of returned materials and supply chain network design. Measurement of environmental objectives was pursued in other relevant literature, evolving around generating renewable energy or minimising the greenhouse gas (GHG) emissions in the transportation of materials and the operation in supply chain procedures. However, this study embraces circularity in Reverse Logistics (RL) model in a standardised way for various construction waste streams. In contrast to the conducted literature analysis, this paper formulates a RL model entailing a material hub which is applied to a combination of different construction and demolition waste (CDW) streams on a municipality scale. This is effectuated by categorising the returned materials in four quality grades (G_1, G_2, G_3, G_4) in the material hub, which correspond to four recovery options (reuse, remanufacture, recycle, landfill), so the materials are transferred accordingly to four actors (new construction projects, remanufacturers, recyclers, landfilling facilities) in the assumed RL. Similarly to relevant studies, the uncertainty in supply-demand quantity is approached with scenario-based methodology, but with diversified supply-demand distributions within the time horizon. The detailed scenario generation is described in Section 6.1.1. Lastly, the quality issues of returned CDW materials in the collection center are addressed by inserting as model inputs certain percentages of returned materials which can be reused, remanufactured, recycled and landfilled based on experts judgement. Those percentages are presented in Section 6.1.2 and are integrated in the model by assuming a symmetric triangular distribution, due to the subjectivity involved in the materials quality expectation.

8.1.2. Practical contributions

In this section, the practical implications of the findings are postulated for Haarlem municipality and for general conditions.

The novelty of this research is the investigation of the financial and circular objectives under diversified patterns of supply and demand for returned materials within a time horizon integrating the uncertainty in quality involved in material streams. In particular, the study provides a clear understanding for decision-makers in Haarlem municipality about the relationship between the supply and demand for returned materials which stimulates profits and circular benefits. Additionally, the outputs of this research should be taken into consideration when decision-makers determine the cost components (storage cost, operational cost, prices that materials are sold to remanufacturers/ recyclers) in projects with similar characteristics. The main practical contribution is the adaptability of the model that is developed in this research. Namely, the fact that the model inputs are integrated in form of ratios allows the easy application of model to different circumstances, e.g. in other municipalities in the Netherlands for different time horizons.

8.2. Findings

In this section, the sub-questions and the main research question are addressed sequentially.

Sub-question 1: What are the key concepts in the identified problem?

Sub-question 1a: What clusters of materials can be used to represent the diverse construction and demolition waste streams in the municipality?

This study considers structures deconstructed on material level. Each construction structure and technique can generate different range of material waste [17]. A research was conducted in the Metropolitan Region of Amsterdam (MRA), in which the materials in 500 buildings were registered after demolition. Based on the occurrence and quantity of materials found, fifteen material clusters were defined: sand and soil, concrete, bricks, stones, ceramics, glass, gypsum, steel and iron, copper, other metals, wood, paper, plastics, bitumen, and isolation material [38]. It is assumed that those material clusters can be also recognised in CDW in other municipalities in the Netherlands.

Sub-question 1b: Which actors can participate in a Reverse Logistics environment for diverse construction and demolition waste streams in the municipality?

Heterogeneity of material characteristics results in different recovery activities and RL can be designed in a different way. This study assumes a RL environment which entails procedures and facilities which are generally applied in the cluster of materials defined in the previous segment. Those treatment options are selected according to R-ladder hierarchy with circular activities found in academic literature [54]. In the material hub, the returned materials are categorised in quality grades which correspond to certain recovery options (reuse, remanufacture, recycle and landfill) and, accordingly, the materials are transferred to respective actors in the assumed RL network (new construction projects, remanufacturers, recyclers and landfilling facilities). In particular, returned materials which can fulfill their original function are in category 1 and are reused directly in new construction projects. Returned materials which can be used in manufacturing of a new product with the same function are in category 2 and are required by remanufacturers. Returned materials which can be processed to obtain the same or lower quality are encompassed in category 3 and are required by recyclers. The returned materials with no residual value are in category 4 and are disposed to landfills.

Sub-question 1c: How circularity can be measured for diverse construction and demolition waste streams in the municipality?

The model embraces circularity based on the integration of the value flow analysis of Circular Economy (CE) in the concept of RL developed by the research team led by Professor Xu Xiao [65]. This theory is associated with two contradicting CE dimensions: resource saving and waste minimisation, but also secondary pollution and environmental deterioration caused by RL operations, such as remanufacturing and recycling [65]. Subsequently, two measurements are defined in the model. The first concept, which is named as circularity, is computed as percentage of returned materials in required materials on new projects. The second aspect is encompassed as the CO_2 emissions from transportation of materials from node to node and the CO_2 emitted in each facility in the assumed network multiplied with quantity of each processed material.

Sub-question 2: What is the proper model to provide a solution in the identified problem?

There are interrelations between RL activities. Therefore, there is necessity for integrated management of the supply chain. Operation Research (OR) models can be applied to solve integrated supply chain management problems considering multiple criteria [52]. So, OR models are identified as the most suitable ones to provide the optimal solution and specifically, inventory and minimum cost flow models in Linear Programming (LP) theory are applicable to the defined problem. The proposed model has the purpose of minimising the cost of material flow in the RL system including the material hub on the municipalities' scale, promoting circularity goals and decreasing the CO_2 rates at the same time. The developed problem is tackled as three-objective multi-product multi-period LP problem and is solved with the ε-constraint method.

Each objective function is expressed as a mathematical function including the decision variables. The decisions variables represent the decisions that should be made in the defined system and are relevant to the quantity of material flows between the facilities included in the assumed RL network. The decision variables should be selected in a way that optimises the objective functions. Furthermore, they are subjected to certain constraints, which are relevant to the capacity in the material hub, flow conservation of material flows between the facilities and the satisfaction of materials demand. The variables in the objective functions and the constraints are combined with the parameters, as inputs to the model. The parameters are constant numbers, which express the rate in which the decision variables affect the objective functions.

Sub-question 3: What is the outcome after applying the model in the municipality of Haarlem?

Sub-question 3a: Which are the circular objectives for cost-effective material flow of construction and demolition waste in the municipality?

The cost-effective material flow is defined by two criteria. Initially, investment in the material hub could evoke cost savings for the municipality as waste management practice in comparison with the current strategy. The second financial criterion is the storage used of materials within two consecutive periods in the material hub. After examination of the model in various scenarios of supply-demand ratio of retuned materials, it is detected that those two financial criteria can be fulfilled in the scenarios with the following supply-demand ratio: 2:1 (S5), 3:1 (S7) and 4:2 (S10). Table 7.16 demonstrates the overall results of cost savings and circular objectives within those scenarios. From Table 7.16, it is observed that the optimal objective values of minimum cost, maximum circularity and minimum CO_2 are not acquired simultaneously in one scenario. Subsequently, the optimal solution is determined depending on the focus of the decision-makers in the municipality.

Sub-question 3b: What are the requirements of the material hub for diverse construction and demolition waste streams in the municipality?

In this study, the requirement of the material hub is the storage capacity for the various waste streams in the hub. The maximum capacity level is initially assumed as the maximum supply of returned materials in one time period. The maximum capacity is halved, but the final cost does not differ substantially. From this analysis, it is concluded that the capacity is not a crucial factor for the financial result, so the range between half and the maximum storage capacity assumed is acceptable for financial viability of the material hub.

Sub-question 3c: Which are the most important factors of influencing costs in the model?

First, the range of materials which can be directly reused and the supply-demand distributions can lead to important variations in the results concerning the financial aspect and the storage level of returned materials in the hub. Moreover, the operational costs, storage costs and prices for which the returned materials are sold to remanufacturers and recyclers are deemed as critical factors for the objective value of cost function. Table 7.15 summarizes the range of critical parameters (in function of the price of newly manufactured materials) in which there are cost savings for the municipality in each scenario.

Main research question: Under which conditions is it profitable for the municipalities in the Netherlands to invest in building a material hub as a waste management strategy, while achieving circular objectives?

The investment in building a material hub is not a sound decision in case that there are less projects which are reaching their end of life cycle and are scheduled to be demolished, than the projects which are planned to be constructed within a time horizon. Additionally, conditions in which supply is higher than demand for returned materials can be favorable for building a material hub as a waste management strategy instead of applying the current practices. It is concluded that in scenarios with supply-demand ratio 2:1 and 3:1, cost savings can reach 2.5-3.6% and 10.8-12% respectively. It can also be stated that even though cost savings are evident under the specific circumstances, they are considered as relatively low considering the initial effort and time of building a material hub.

8.3. Recommendations for further research

In this research, various simplifications were made which are acknowledged in this section and accompanied by relevant future directions for work.

1. The transportation costs were divided in transportation costs of returned materials transferred through the hub and transportation costs of new materials transferred from outsourcing nodes. As simplification, the distances between the model nodes were omitted which might affect the financial result. The model should be tested in a case in which location of the facilities is known and the transportation costs are in function of the actual distance.

2. Approximations associated with the cost components can influence the results. Some simplifications were leading to less favorable results and others not. For example, in this study, materials were treated and transferred separately. But in reality, certain materials are transferred together and might induce less cost and $C0_2$ emissions. On the other hand, the material prices fluctuated but with rising trends. The case that materials prices can drop was not examined which might influence the end result in such a level that returned materials are not preferred. Those assumptions can be reviewed in future research.

3. The model results were compared with the benchmark of current waste management situation which is deemed as conservative. Detailed research should be conducted about the costs incurred in the current waste management practices in Haarlem municipality. This information is crucial because if the benchmark is changed tremendously, no favorable output might be induced.

4. This research was limited in the municipality region, which might be regarded as small sample size regarding the materials quantities. The model can be extended in the future to consider more municipalities and focus on how the municipalities can collaborate at national level for circular waste management.

5. In practice, materials from remanufacturers and recyclers can be transferred back to the material hub, to new projects or to outsourcing facilities (manufacturers) and then be stored until demand for them arises. This is beyond the scope of this study, so future studies are needed to establish that the system does not end in the demand nodes in the assumed model and includes more technical cycles of construction materials.

A

Literature review in Reverse Logistics models

The papers reviewed have been categorised based on their model characteristics, the modelling technique and solution method followed.

Table A.1: Literature review in Reverse Logistics models

Paper	**Supply Chain**	**Objective**	**Material**	**Time period**	**Capacity & Location of processing facilities**	**Demand for returned materials**	**Supply of returned materials**	**Quality of returned materials**	**Solution method**	**Solver**
[11]	Reverse Logistics	Single	Multiple	Multiple	Certain	Uncertain	Uncertain	Uncertain	LP [a]	Not defined
[14]	Closed- loop	Multiple	Multiple	Single	Uncertain	Certain	Uncertain	Uncertain	Two-stage stochastic programming	Heuristic and meta-heuristic algorithms
[29]	Reverse Logistics	Single	Multiple	Single	Uncertain	Certain	Certain	Certain	MILP [b]	LINGO
[32]	Closed- loop	Single	Multiple	Single	Uncertain	Uncertain	Uncertain	Uncertain	Robust programming	CPLEX
[35]	Reverse Logistics	Single	Multiple	Multiple	Uncertain	Certain	Uncertain	Uncertain	Fuzzy mathematical programming	Zimmermann algorithm
[36]	Reverse Logistics	Single	Multiple	Single	Uncertain	Certain	Uncertain	Certain	MINLP [c]	Hybrid GA [d]
[40]	Reverse Logistics	Multiple	Multiple	Single	Certain	Certain	Certain	Certain	MILP	Excel Solver
[51]	Closed- loop	Single	Multiple	Single	Certain	Certain	Certain	Uncertain	Robust programming	CPLEX
[53]	Closed- loop	Single	Multiple	Multiple	Certain	Uncertain	Uncertain	Uncertain	MILP	CPLEX
[55]	Reverse Logistics	Single	Single	Single	Uncertain	Uncertain	Uncertain	Uncertain	MILP with scenarios	Not defined
[63]	Reverse Logistics	Multiple	Multiple	Single	Uncertain	Uncertain	Uncertain	Uncertain	Stochastic MOMIP [e]	LINGO
[65]	Reverse Logistics	Single	Multiple	Single	Certain	Certain	Certain	Certain	ILP [f]	LINGO
This study	Reverse Logistics	Multiple	Multiple	Single	Certain	Certain	Certain	Uncertain	MILP	CPLEX

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[a] LP=Linear Programming

[b] MILP= Mixed Integer Linear Programming

[c] MINLP=Mixed Integer Non-Linear Programming

[d] GA= Genetic Algorithm

[e] MOMIP=Multi-Objective Mixed Integer Programming

[f] ILP=Integer Linear Programming

B

Linear Programming Theory

A Reverse Logistics (RL) model is proposed as the solution to evaluate the impact of the material hub as a circular waste management strategy. A RL supply chain is considered as a network of facilities in which the materials from the consumption points are distributed to the points of origin [26]. Since there are interrelations between those facilities, there is necessity for integrated management of the supply chain. Operation Research (OR) techniques can be applied to solve integrated supply chain management problems. Linear programming (LP) has been selected as the most suitable modelling approach for the problem postulated. Multiple LP problems addressed RL issues, aiming in planning the RL activities in such a way that the optimal result in terms of maximum profits (financial, environmental or social) should be achieved. Particularly, the problem formulation is based on the theory about inventory and minimum cost flow models, so this appendix entails the principles of LP and characteristics of those types of models.

B.1. Linear Programming

In general terms, LP is identified as a valuable tool for advising the key decision-makers about their managerial techniques. This method can define a range of optimal management alternatives under different assumptions, which can constitute the departure point for improvements in the current strategies used. The main type of application of LP problems is the allocation of limited resources m among competing activities j in the optimal way [24, p.32].

The mathematical model of the aforementioned problem is formulated as follows [24].

The objective function (which should be maximised or minimised) has this mathematical formulation:

$$Z = c_1 x_1 + c_2 x_2 + ... + c_n x_n$$

where x$_j$ = decision variable which shows the level of activity $j (for j = 1, 2, ..., n)$

c$_j$ = parameter (coefficient) which depicts the contribution of activity j to the objective function Z

The objective function is subject to constrains:

$$a_{11} x_1 + a_{12} x_2 + ... + a_{1n} x_n \geq b_1$$

$$a_{21} x_2 + a_{22} x_2 + ... + a_{2n} x_n \geq b_2$$

$$a_{m1} x_n + a_{m2} x_n + ... + a_{mn} x_n \geq b_n$$

where b$_i$=parameter which presents the amount of resource i that is available for allocation to activities $(for\ i = 1, 2, ..., m)$

a$_{ij}$=parameter (coefficient) which presents the amount of resource i consumed by each unit of activity j

There can also be non-negative constraints:

$$x_n \geq 0$$

LP applies for a problem when the following assumptions are met [24, p.36]:

1. Proportionality: Change in the level of each activity (coefficients c_j, a_{ij}) can proportionately change its contribution in the objective function and its contribution to the constraints.
2. Additivity: Every function in LP is the sum of the individual contribution of each activity.
3. Divisibility: Decision variables can have any values (even non-integer values) that satisfy the constraints.
4. Certainty: The value of each parameter is assumed to be a known constant.

B.2. Inventory models

Managing inventories is essential for any company in construction sector which is related to physical products. The cost associated with storing of inventories can be substantial. So reducing the storage costs by eliminating large inventories can make the company more competitive. Among the OR techniques, the inventory management technique can be a tool to improve the inventory system in an optimal way. The basic components for inventory optimisation models are briefly elaborated below [24, p.938]:

1. Ordering cost
2. Holding cost

   All the cost involved in storage of materials until they can be used or sold. Those costs can be the investment capital and space/ insurance/ protection/ storage taxes. These holding costs can be calculated either continuously or in a period-by-period basis. The most common assumptions are that the holding costs are accounted in periods, as cost in function of maximum/ average quantity of materials held during each period or in function of quantity in inventory at the end of each period.

3. Shortage cost

   The unsatisfied demand cost which occurs in case that the demand exceeds the quantity of materials in the inventory. In this case, the cost is calculated based on two different cases.1) Backlogging: The excess demand is not met in a specific time period, but it is satisfied in the next time period that materials are produced. 2) In case of no backlogging, there is no waiting period until the next time period, so the materials can meet the excess demand. That means that the demand is met by priority shipment or it is not met at all because the orders are cancelled.

4. Revenue from sales

   If both the price and the demand for the product in demand nodes are defined by the firm and not the market, the revenues should be integrated.

5. Salvage value

   The value of the remaining materials in the inventory which may be disposed in the market with a discount.

6. Lead time

   Time between placing an order and the delivery of the materials.

7. Facility operating costs:

   - facility depreciation costs (facility construction costs and expected life span)

     The value of money is depreciated in different time periods. When the firm is investing in construction of inventory implies that the company is prevented to use the same capital for alternative secure investments. In order to integrate this risk and find the net present value of profit for each period, the profit in every time period should be multiplied with a discount factor.

- maintenance costs
- personnel costs [63]

Those types of models can be classified in the following categories according to Hillier & Lieberman [24].

1. Deterministic inventory model/ Stochastic inventory model

   The inventory models can be deterministic or stochastic models, according to the predictability of parameters involved in each problem. In inventory problems, one of the most common variables is the demand. In case the demand for products can be forecasted with precision during a specific time period, it is assumed that the demand is certain, so a deterministic model can be used. In the other hand, if the demand in any period is not a certain parameter but a random variable having a known probability distribution, a stochastic version of inventory model is preferred.

2. Single-Echelon model/ Multi-Echelon model

   In contrary to the single-echelon inventory system, in multi-echelon inventory systems, the materials are passing through various facilities and the material flow coming in and out from those facilities is considered in the model.

3. Inventory level is monitored continuously or periodically

   In continuous base, the materials are ordered once the demand is satisfied, while in periodic base, the rate of products are ordered in discrete time periods even though the demand is not satisfied between the previous and following time period.

B.3. Minimum cost flow models

According to Hillier & Lieberman [24, p.429], the minimum cost flow problem considers flow assigned with cost through a network with limited arc capacities. Multiple supply nodes and demand nodes can be included in the network flow.

The main characteristics of the model are:

1. The network is a directed and connected network.
2. At least one of the nodes is a supply node.
3. At least one of the other nodes is a demand node.
4. All the remaining nodes are transshipment nodes.
5. Flow through an arc is allowed only in the direction indicated by the arrowhead, where the maximum amount of flow is given by the capacity of that arc.
6. The network has enough arcs with sufficient capacity to enable all the flow generated at the supply nodes to reach all the demand nodes.
7. The cost of the flow through each arc is proportional to the amount of that flow, where the cost per unit flow is known.
8. The objective is to minimize the total cost of sending the available supply through the network to satisfy the given demand. (An alternative objective is to maximize the total profit from doing this.)

The mathematical model of the aforementioned problem is formulated as follows [24, p.431]. Consider a directed and connected network where the n nodes include at least one supply node and at least one demand node. The decision variables are:

$x_{ij} = flow\ through\ arc\ i \rightarrow j$

and the given information includes

$c_{ij} = cost\ per\ unit\ flow\ through\ arc\ i \rightarrow j$

$u_{ij} = arc\ capacity\ for\ arc\ i \rightarrow j$

$b_i = net\, flow\, generated\, at\, node\, i$

The value of b_i depends on the nature of node i, where

$b_i > 0\; if\; node\; i\; is\; a\; supply\; node,$

$b_i < 0\; if\; node\; i\; is\; a\; demand node,$

$b_i = 0\; if\; node\; i\; is\; a\; transshipment\; node.$

The objective is to minimize the total cost of sending the available supply through the network to satisfy the given demand. By using the convention that summations are taken only over existing arcs, the linear programming formulation of this problem is

$$Minimize\, Z = \sum_{i \in N} \sum_{j \in N} x_{ij} c_{ij}$$

$$subject\; to$$

$$\sum_{i \in N} x_{ij} - \sum_{j \in N} x_{ij} = b_i \quad for\; each\; node\; i$$

$$And$$

$$0 \leq x_{ij} \leq u_{ij}, \quad for\; each\; arc\; i \rightarrow j$$

The first summation in the node constraints represents the total flow out of node i, whereas the second summation represents the total flow into node i, so the difference is the net flow generated at this node.

B.4. ε-constraint method

A three-objective optimization problem arises, since the decision-makers consider three conflicting objectives: minimizing cost, maximizing circularity and minimizing CO_2 rates. The competing objectives cannot be satisfied simultaneously but there are multiple optimal solutions, the Pareto optimal solutions, which aim in optimal value of one objective function without deteriorating the value of the other objective functions. The illustration of the set of Pareto optimal solutions can formulate the efficient frontier which will be the end result of the research. The approach selected to provide a solution in this three-objective problem is the ε-constraint method [20].

Within this methodology there are two ways to formulate the Pareto optimal solutions: the conventional and the lexicographic method. The lexicographic method is applied in which the objective functions are ranked based on their importance and each objective function is satisfied individually subjected to constraints which enforce the values of the higher ranked objective functions remain close to their optimal values [49]. To illustrate an example, for the case of two objective functions, supposing f_1 is higher ranked than f_2, the optimal objective value of f_1' is found. Secondly, the optimal objective function of f_2 is investigated based on the additional constraint of not sacrificing more than a certain percentage (ε) the optimal value of f_1' [20].

1. $min f_1(x) = f_1'$
   subject to $x \in \Omega$

2. $min f_2(x)$
   subject to $x \in \Omega$
   $f_1(x) \leq f_1' * \varepsilon$

C

Exploratory discussion with Haarlem municipality

Inventory discussion took place for investigating the current waste management practices within the Haarlem municipality. The following open questions were posed to Alex Jansen and Martijn van Minderhout, Project Managers in Haarlem municipality.

General	1. Which are the current Circular Economy practices? 2. What kind of assets are processed? Infrastructure assets or buildings?
Supply chain	3. Which are the current Reverse Logistics practices? 4. Are returned materials collected in collection centres/ hubs? 5. Is there any storage facility? 6. Which are the processing facilities considered in the vicinity area? (remanufacturers/ recyclers/ landfills) 7. Is there necessity for new materials in new projects or are returned materials sufficient to match the demand?
Material flow	8. Is there information about the location of the End of life cycle infrastructure assets? (supply) 9. Is there information about the quantity/quality of returned materials after the demolition? (supply) 10. Is there information about the period those returned products are available? (supply) 11. Is there information about the quantity/quality of materials needed for new projects and in which period? (demand) 12. Is the location of processing facilities known? 13. How the asset is processed? Is the asset dismantled into components/ materials? 14. Does the separation of materials happen in the demolition site or in a processing facility/hub? 15. Should the returned components/materials be stored before being processed or can they be directly used? 16. Which are the possible options for transportation?

D

Exploratory discussions/ Questionnaires about the conceptual framework of model

The conceptual framework of the model was developed combining information derived by both primary (interviews/questionnaires) and secondary sources (research studies conducted in the past). In this section, the way information was collected by primary sources is presented.

Data gathering was conducted with the method of structured interviews (person-to-person interaction) and questionnaires with open-ended questions. In the interview, more in depth information could have been obtained in comparison with questionnaires. However, questionnaires were sent by emails because of some interviewees' preference.

Regarding the exploratory discussions, a list of questions, the ''interview guide" was prepared with the topics which will be discussed with interviewees. This guide was used as the core of the discussion, however the respondents were encouraged during the interview to add experiences and understandings in relation to the topic [34].

In questionnaire, there is the challenge that the respondent misunderstands the interviewer's question since there is no margin for explanation of questions. In case of misinterpretation, the quality of information collected may be influenced [34]. This is why attention was given in the phrasing and sequence of questions, so they could have been comprehensible by the respondent. The questionnaire was also formulated in an interactive way with a further explanation of the question in a font, so there was full comprehension of questions. Disadvantage of method of questionnaire is that supplementary questions cannot be drawn, since there is specific list of questions [34].

The focus of both methods is to obtain an insight in the practise of waste management for materials from infrastructure assets and buildings and to gain information about decisions for supply chain management of construction and demolition waste, about material hub characteristics and expected quality of materials after demolition.

Table D.1: List of interviewees/ respondents

Name	**Organisation**	**Data gathering method**
René Helder	Building Advisor in Antea Group	Exploratory discussion
Jan-Lucas Hof	Building Project Manager in Antea Group	Exploratory discussion
Henk Verschuuren	Project Leader in Antea Group	Exploratory discussion
Wiersum Guido	Contract Advisor in Antea Group	Exploratory discussion
Frank Rens	Project Leader in GBN	Questionnaire
Edwin Zoontjes	Advisor and Project Manager in MiSa Advies	Questionnaire
Harry Hofman	Director of Circularity in Raw Materials in GBN and C2CA Technology B.V., Project Manager in Strukton	Questionnaire

Table D.2: Interview guide/ Questionnaire

Waste management / Materials hub operations
1. Is there a generic procedure after demolition of projects and before distributing the returned products to the clients? *The characteristics in waste streams can vary. For instance, the glass is treated in another way than wood. However, I am wondering if there are standard steps to process materials independently on their diverse nature.*
2. How do you define the actors in supply chain for the returned products? *Every product can be sold to different clients. This question is relevant to the criteria before deciding which will be the clients of returned products. For instance, do you develop business models to convert waste streams to valuable products before the demolition? If yes, which are the considerations?*
3. How do you define a demolition plan for a project? *I am wondering if products are dismantled into components/ materials. If yes, does this separation happen in the demolition site or in a processing facility? All these decisions are taken based on demand specificities?*
4. How materials are transferred after demolition? *I am wondering if materials are transferred separately or together with other materials, in modules or not.*
5. How the products after demolition are treated? *Some relevant questions are posed to supplement the main question. Should the products be stored before being processed or can be directly used? Are the products categorised based on their quality before being distributed in the market? If yes, which is the procedure of this categorisation?*
6. Do you find essential to store the products in hubs? If yes, why? (if there is relevant knowledge)
7. Which are the operations required for a material hub and which are the characteristics of a hub lay-out? (if there is relevant knowledge) *To give you an example, some operations can be collection, inspection, treatment, categorisation, storage of materials. Regarding the second section of question, there may be necessity for different storing capacity for each material type or space for equipment.*

<table>
<tr><th colspan="5">**Expected quality of materials after demolition**</th></tr>
<tr><td colspan="5">Which is the expected condition of the following fifteen materials (sand and soil, concrete, bricks, stones, ceramics, glass, gypsum, steel and iron, copper, other metals, wood, paper, plastics, bitumen and isolation material) after deconstruction of projects?
In order to answer this question, I am asking you to fill the following table. Since there cannot be only a concrete answer given the uncertainty involved after the of projects, you can provide a range of those percentages.
(For clarification reasons, I provide the following example. There is knowledge that in a project there is a certain amount of steel bars before the deconstruction. After the deconstruction of this project, which percentage of those products is expected to be reused, remanufactured, recycled and/or landfilled?)</td></tr>
<tr><td>Clusters of materials</td><td>Percentage of materials which can be reused (%)</td><td>Percentage of materials which can be remanufactured (%)</td><td>Percentage of materials which can be recycled (%)</td><td>Percentage of materials with no further value (%)</td></tr>
<tr><td>sand and soil</td><td></td><td></td><td></td><td></td></tr>
<tr><td>concrete</td><td></td><td></td><td></td><td></td></tr>
<tr><td>bricks</td><td></td><td></td><td></td><td></td></tr>
<tr><td>stones</td><td></td><td></td><td></td><td></td></tr>
<tr><td>ceramics</td><td></td><td></td><td></td><td></td></tr>
<tr><td>glass</td><td></td><td></td><td></td><td></td></tr>
<tr><td>gypsum</td><td></td><td></td><td></td><td></td></tr>
<tr><td>steel and iron</td><td></td><td></td><td></td><td></td></tr>
<tr><td>copper</td><td></td><td></td><td></td><td></td></tr>
<tr><td>other metals</td><td></td><td></td><td></td><td></td></tr>
<tr><td>wood</td><td></td><td></td><td></td><td></td></tr>
<tr><td>paper</td><td></td><td></td><td></td><td></td></tr>
<tr><td>plastics</td><td></td><td></td><td></td><td></td></tr>
<tr><td>bitumen</td><td></td><td></td><td></td><td></td></tr>
<tr><td>isolation material</td><td></td><td></td><td></td><td></td></tr>
</table>

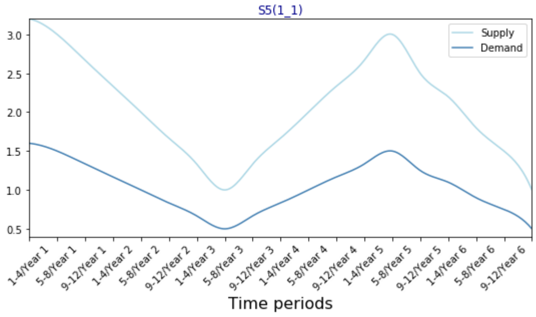
E

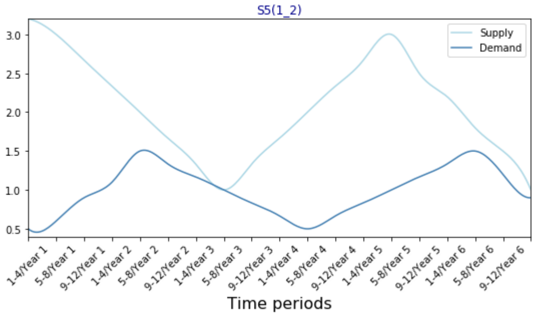
Sets of instances

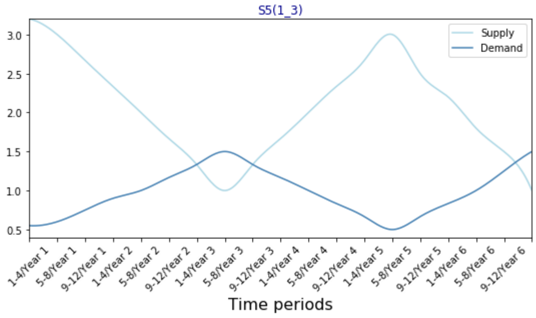
Scenarios generation is conducted for the model inputs of supply and demand for materials. Sixteen sets of instances of supply-demand dynamics during the time horizon are formulated per scenario which are visualised in the following section.

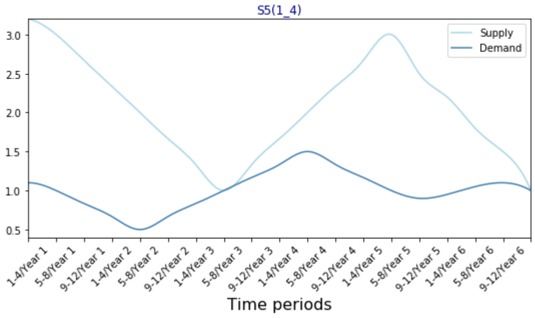
Scenario S5

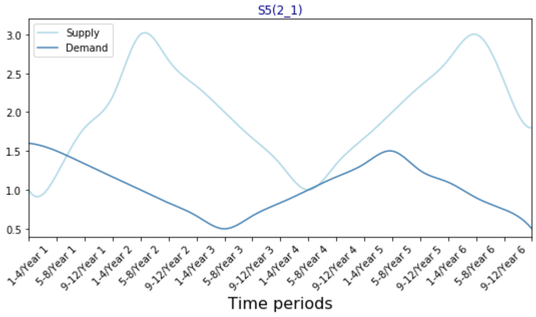
In scenario S5, the sets of instances of supply-demand fluctuation are illustrated in the line plots below (Figure E.8).

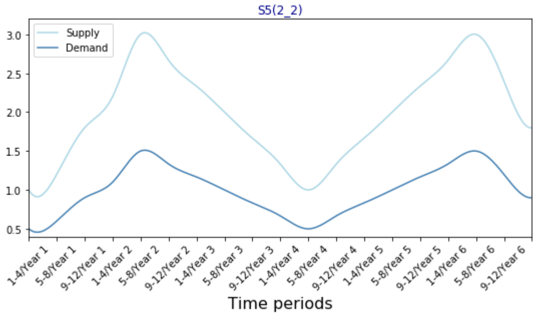


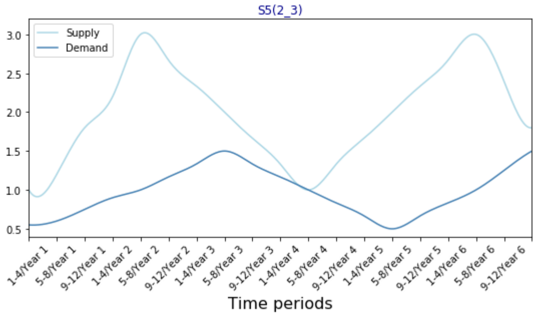


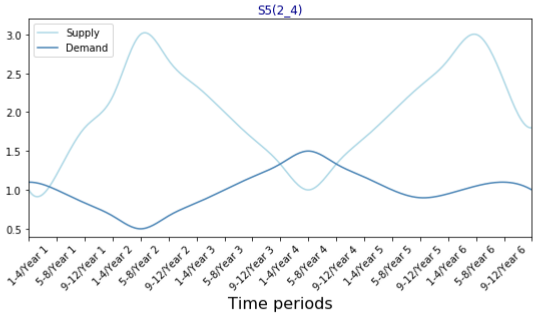


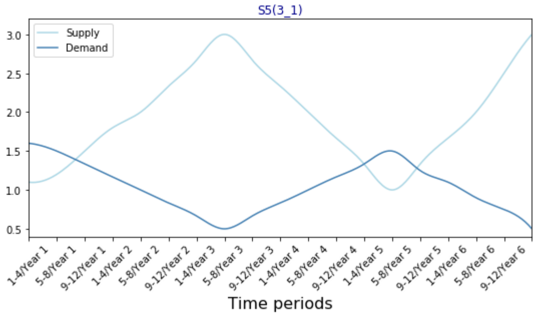


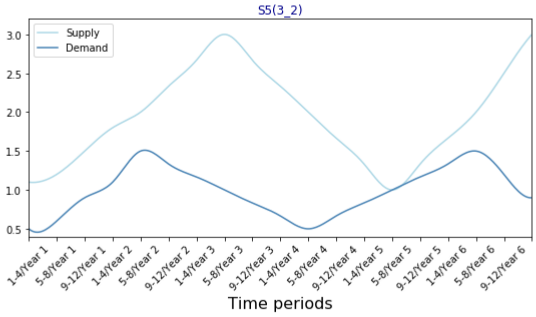

S5(2_1)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods

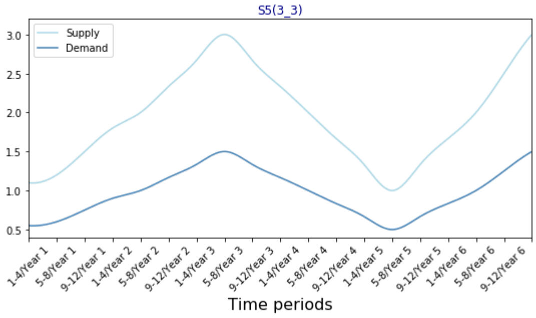

S5(2_2)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods

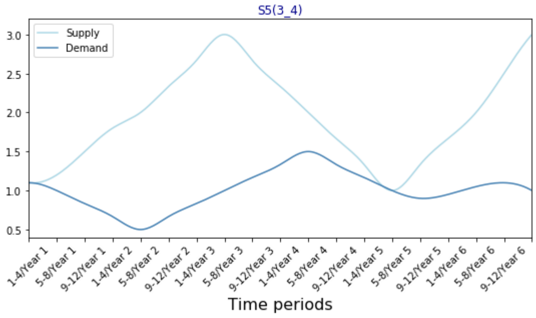

S5(2_3)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S5(2_4)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S5(3_1)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S5(3_2)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S5(3_3)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S5(3_4)
Supply
Demand
3.0
2.5
2.0
1.5
1.0
0.5
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods

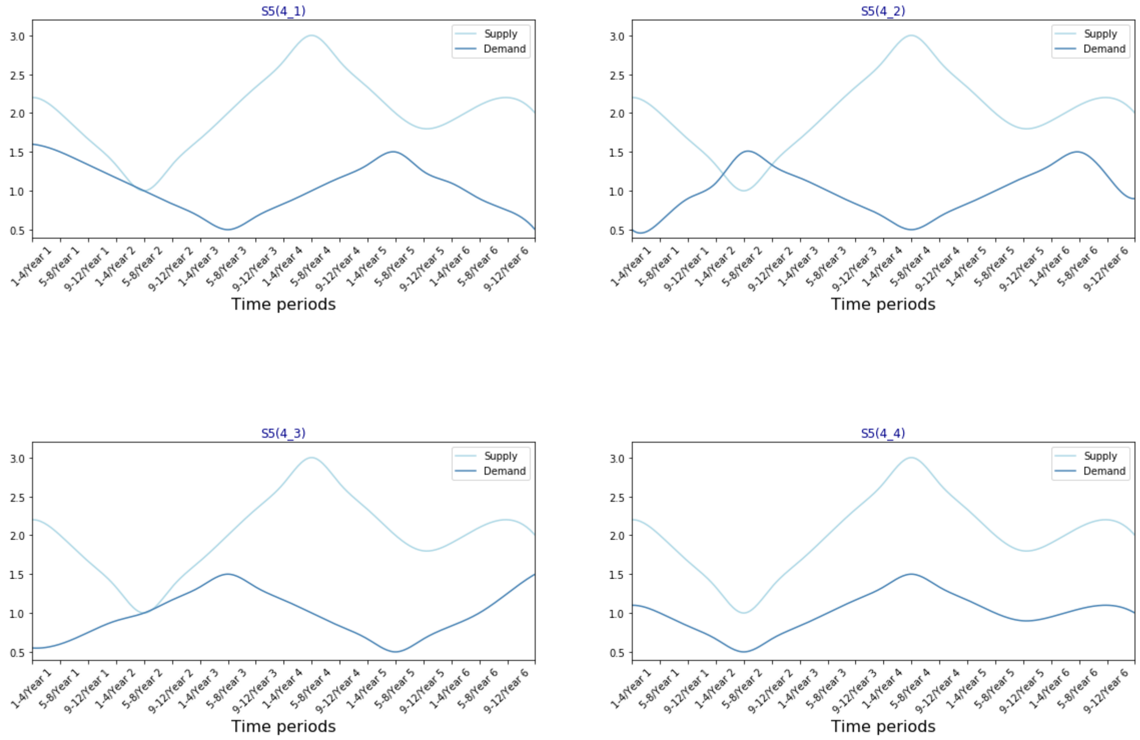
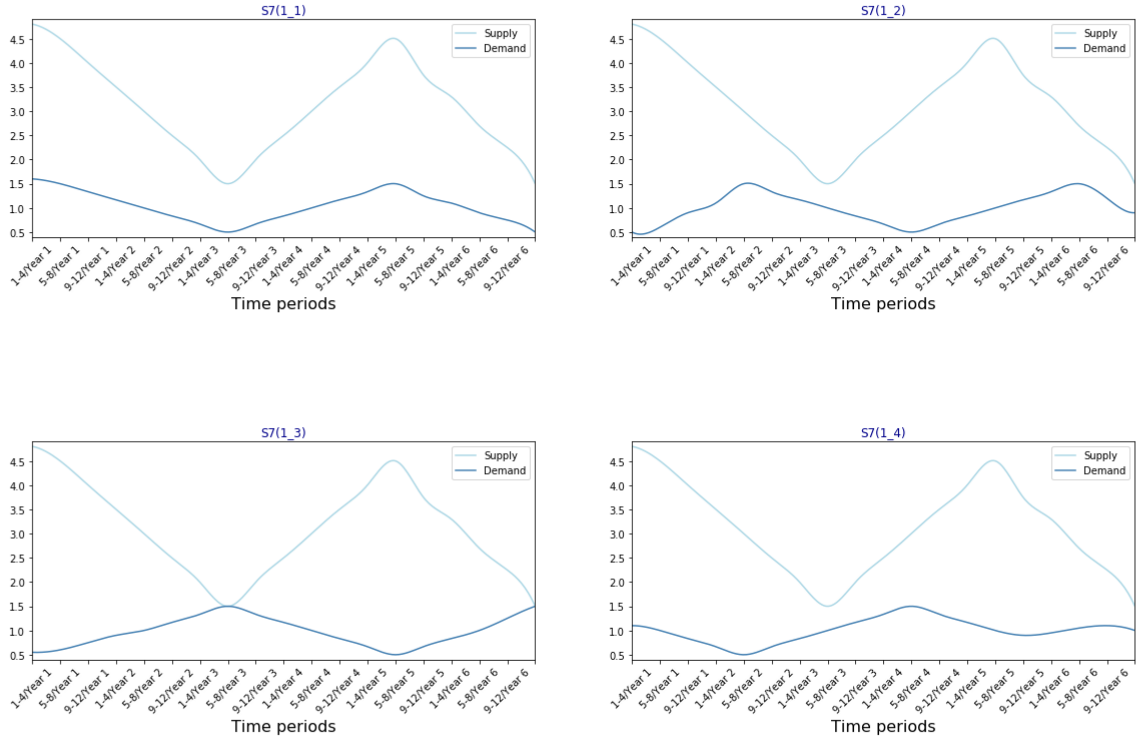
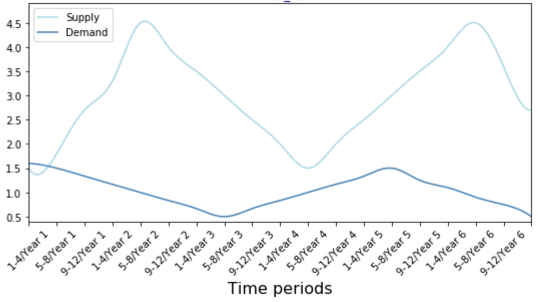


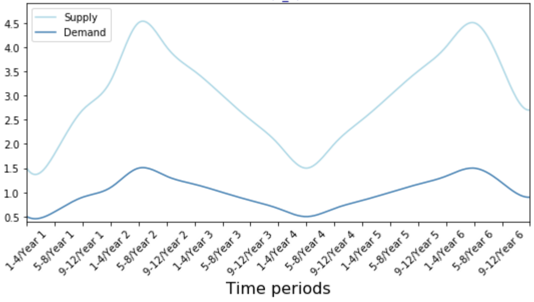
Figure E.8: Sets of instances in scenario S5

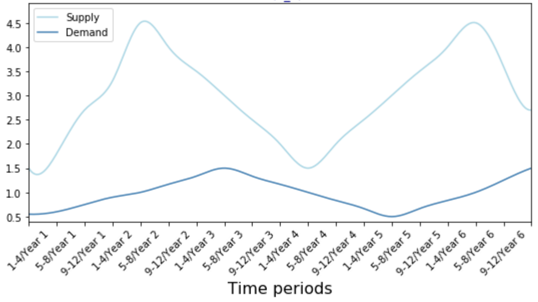
Scenario S7

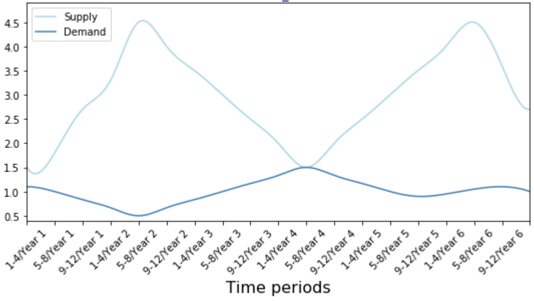
In scenario S7, the sets of instances of supply-demand fluctuation are presented in the line plots below (Figure E.16) .

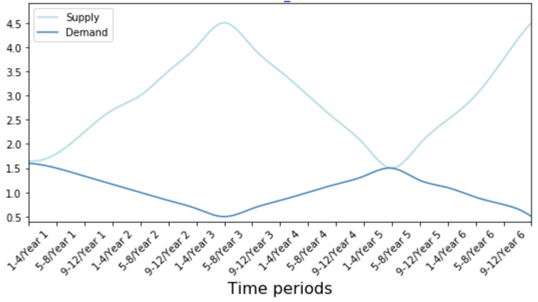


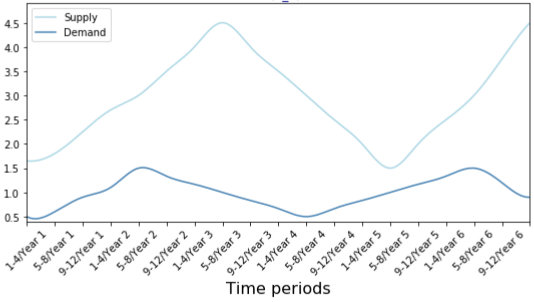

S7(2_1)

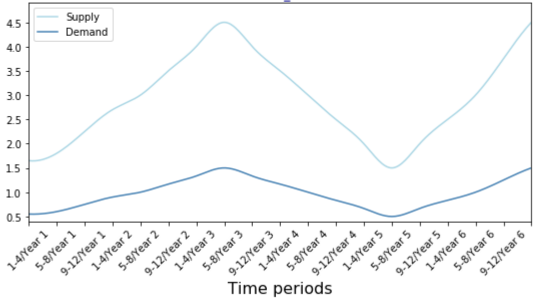

S7(2_2)

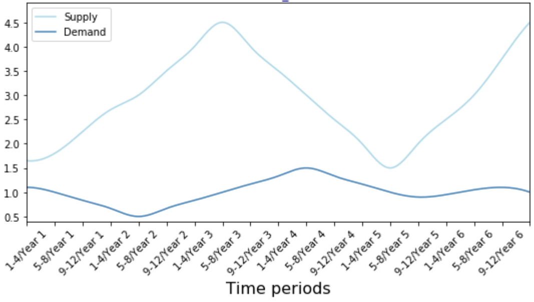

S7(2_3)


S7(2_4)


S7(3_1)


S7(3_2)


S7(3_3)


S7(3_4)

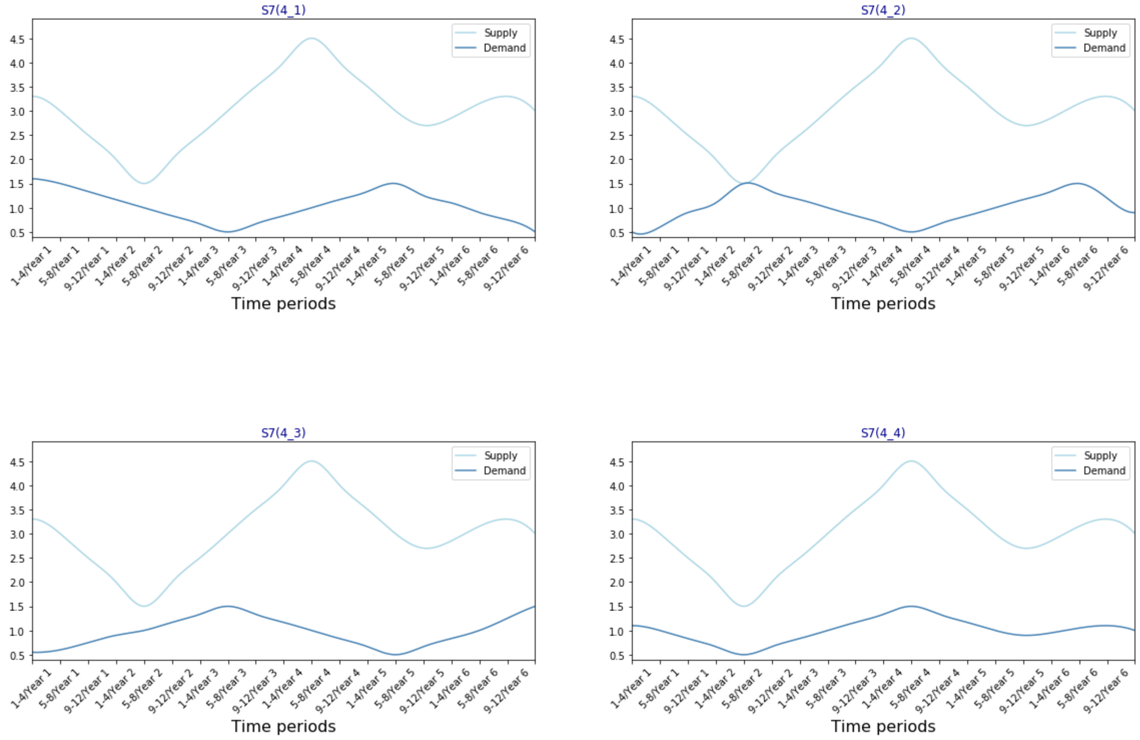
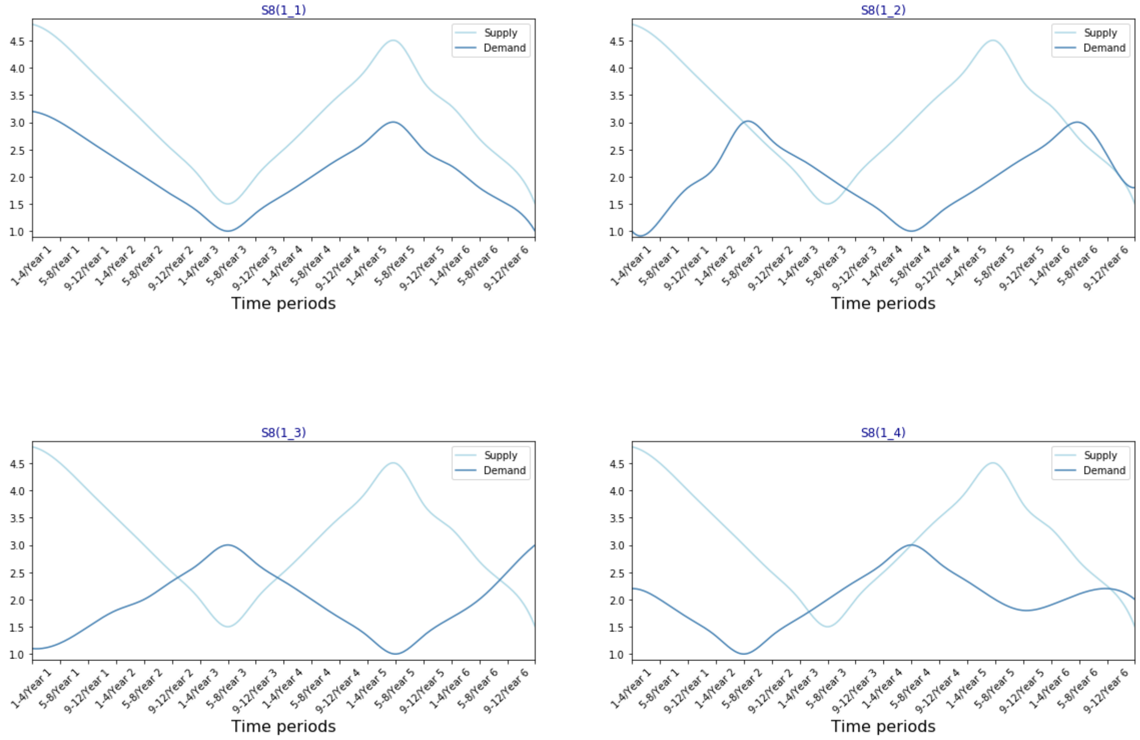
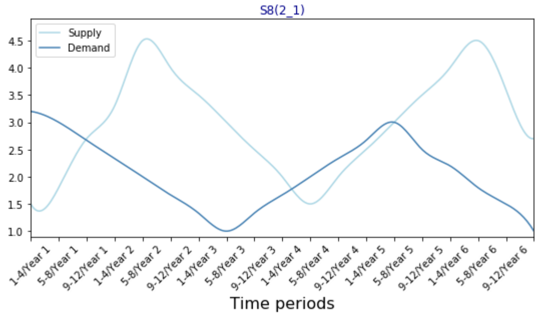


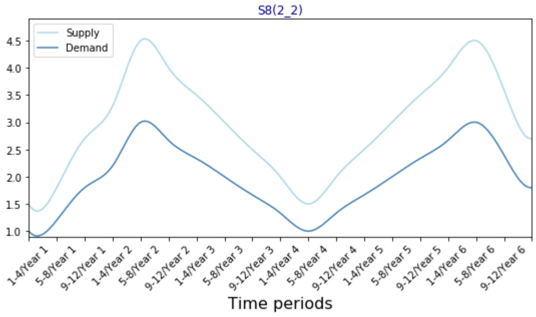
Figure E.16: Sets of instances in scenario S7

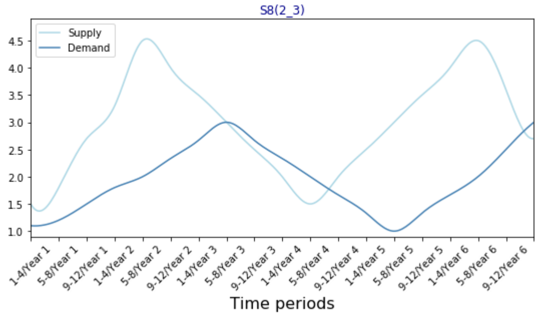
Scenario S8

In scenario S8, the sets of instances of supply-demand fluctuation are elaborated in the line plots below (Figure E.24).




S8(2_1)


S8(2_2)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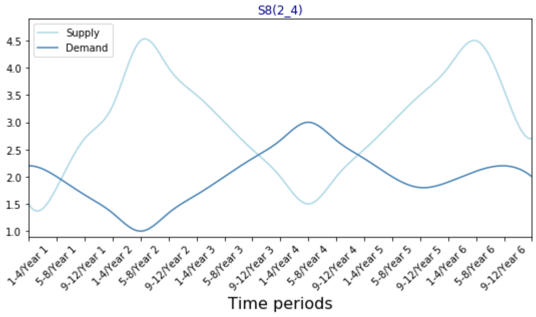
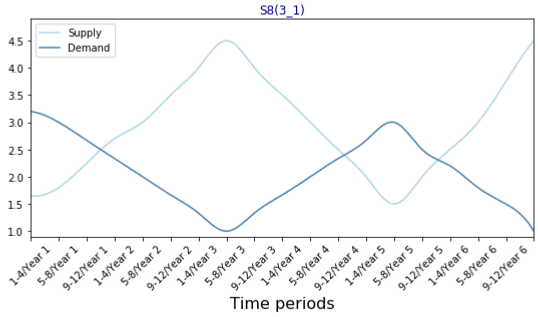
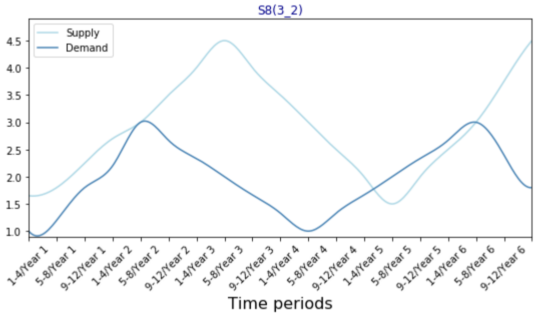

S8(2_4)


S8(3_1)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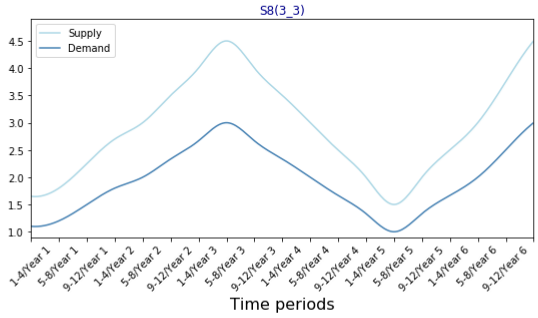
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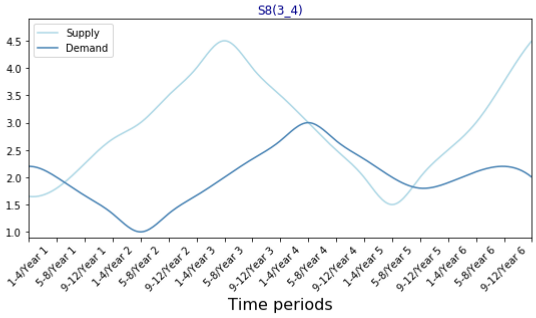
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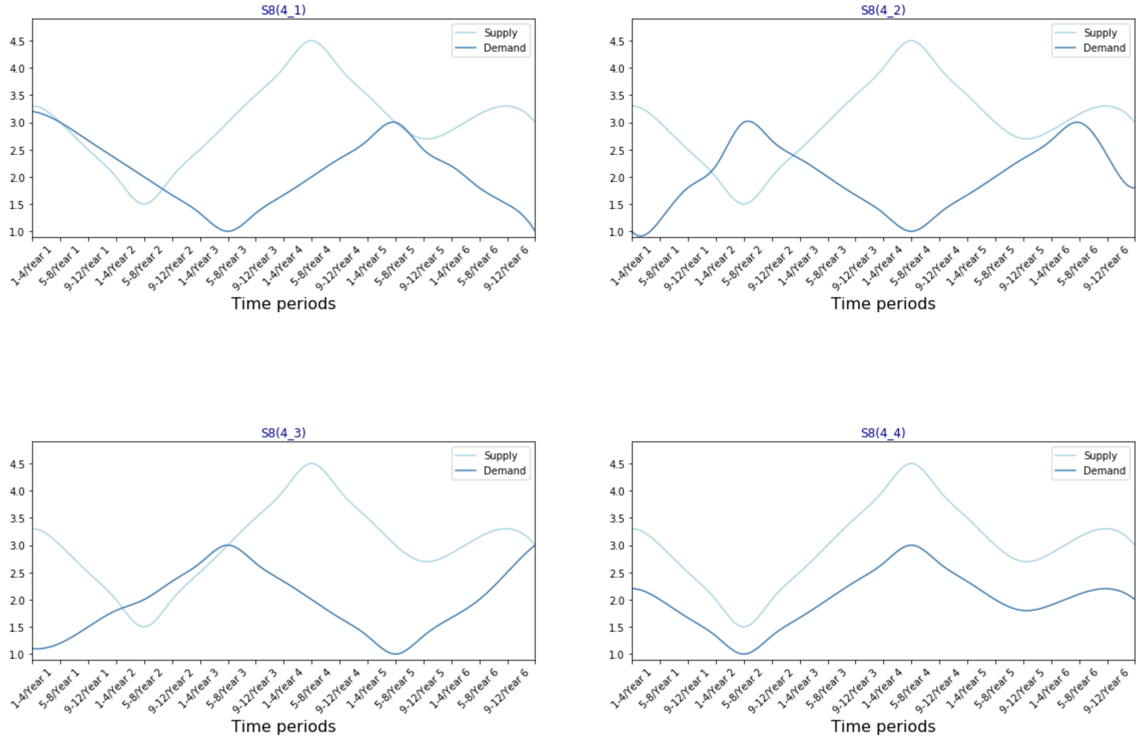
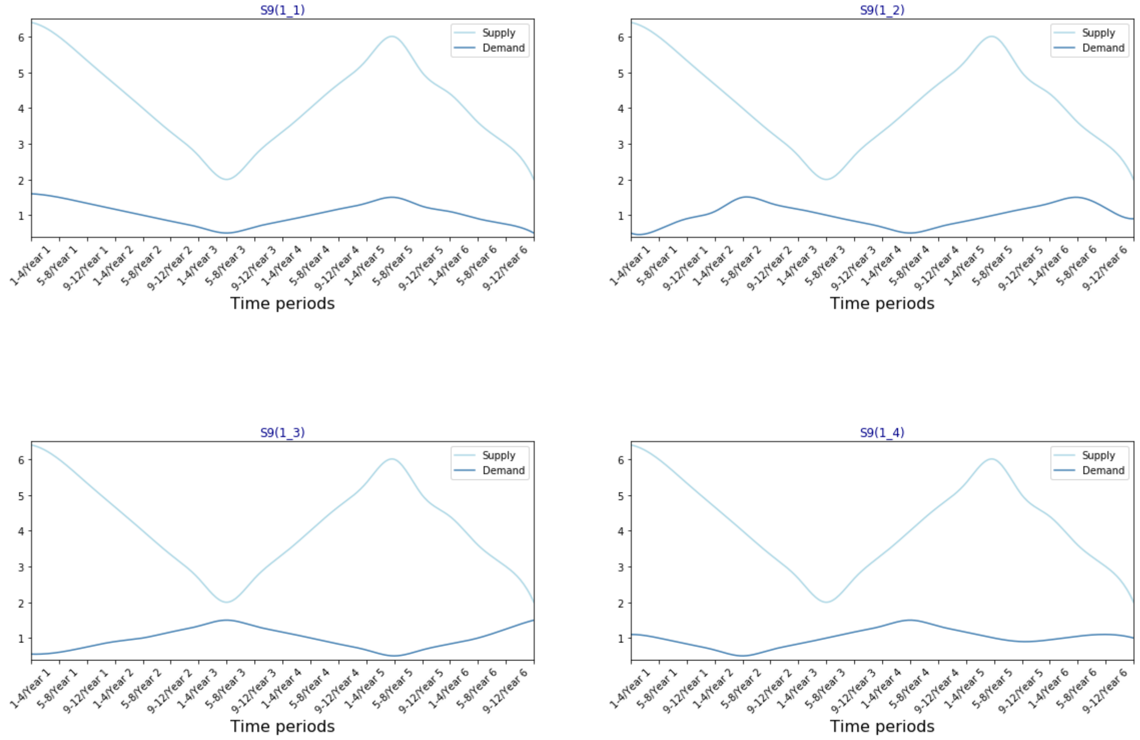
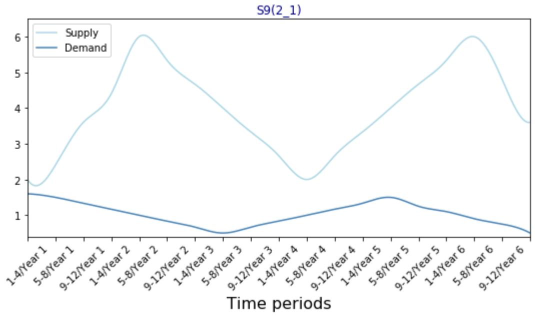


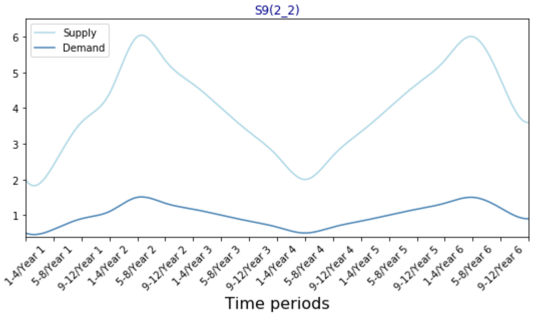
Figure E.24: Sets of instances in scenario S8

<u>Scenario S9</u>

In scenario S9, the sets of instances of supply-demand fluctuation are depicted in the line plots below (Figure E.32).




S9(2_1)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S9(2_2)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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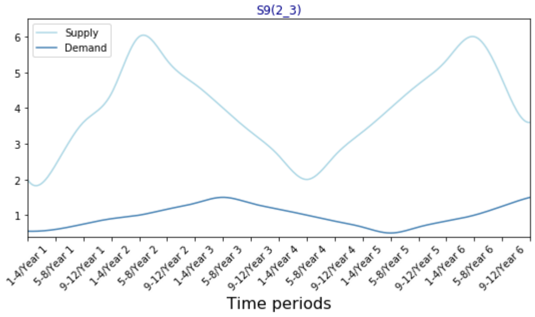
5-8/Year 6
9-12/Year 6
Time periods


S9(2_3)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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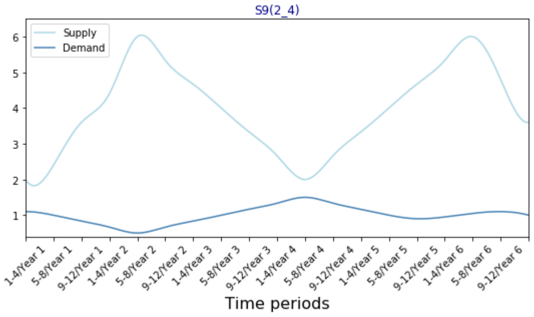
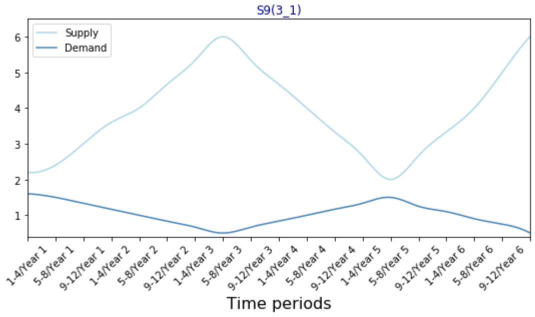
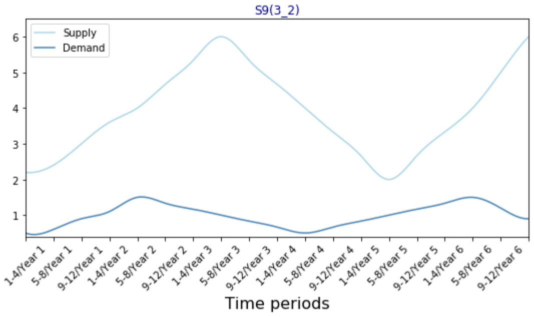
5-8/Year 6
9-12/Year 6
Time periods


S9(2_4)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S9(3_1)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S9(3_2)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
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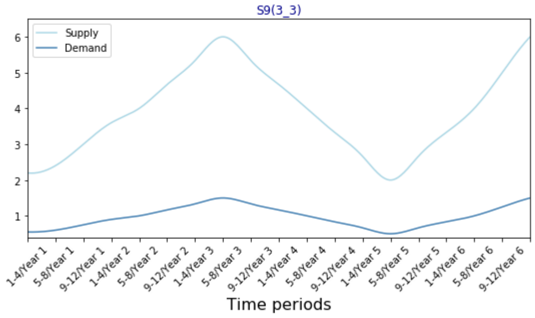
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S9(3_3)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
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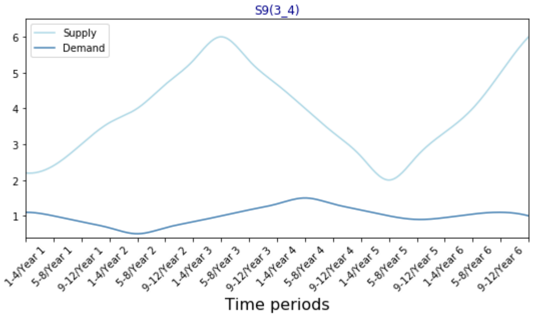
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S9(3_4)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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5-8/Year 6
9-12/Year 6
Time periods

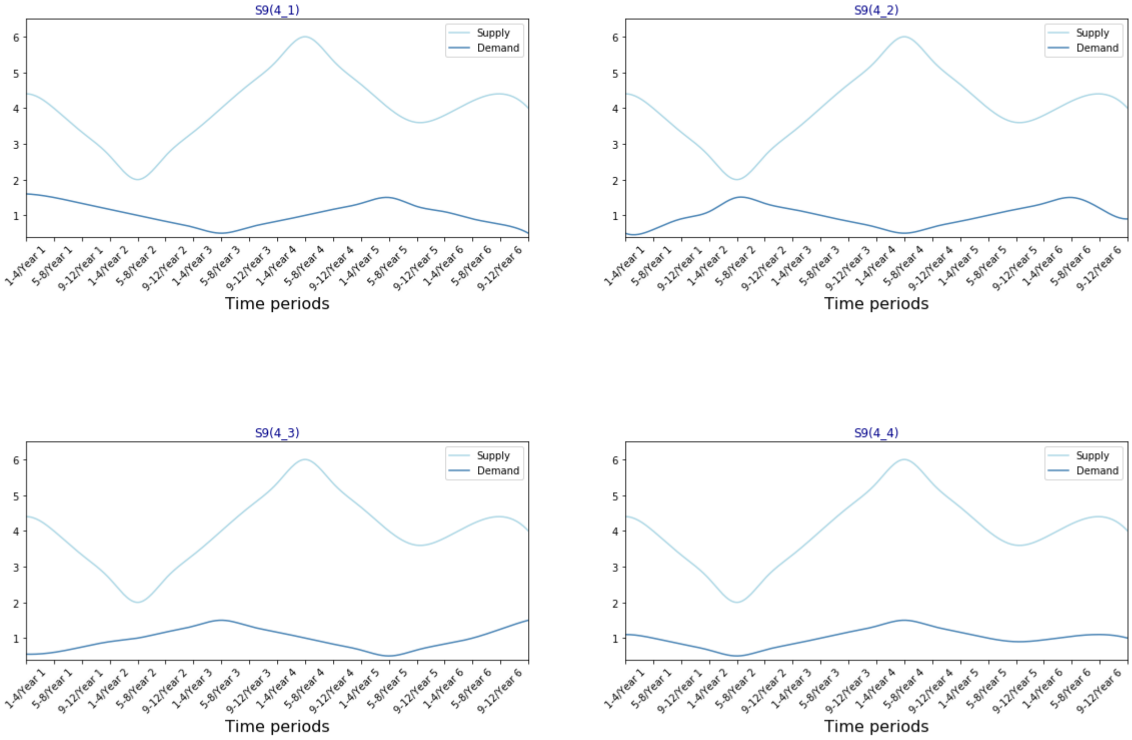
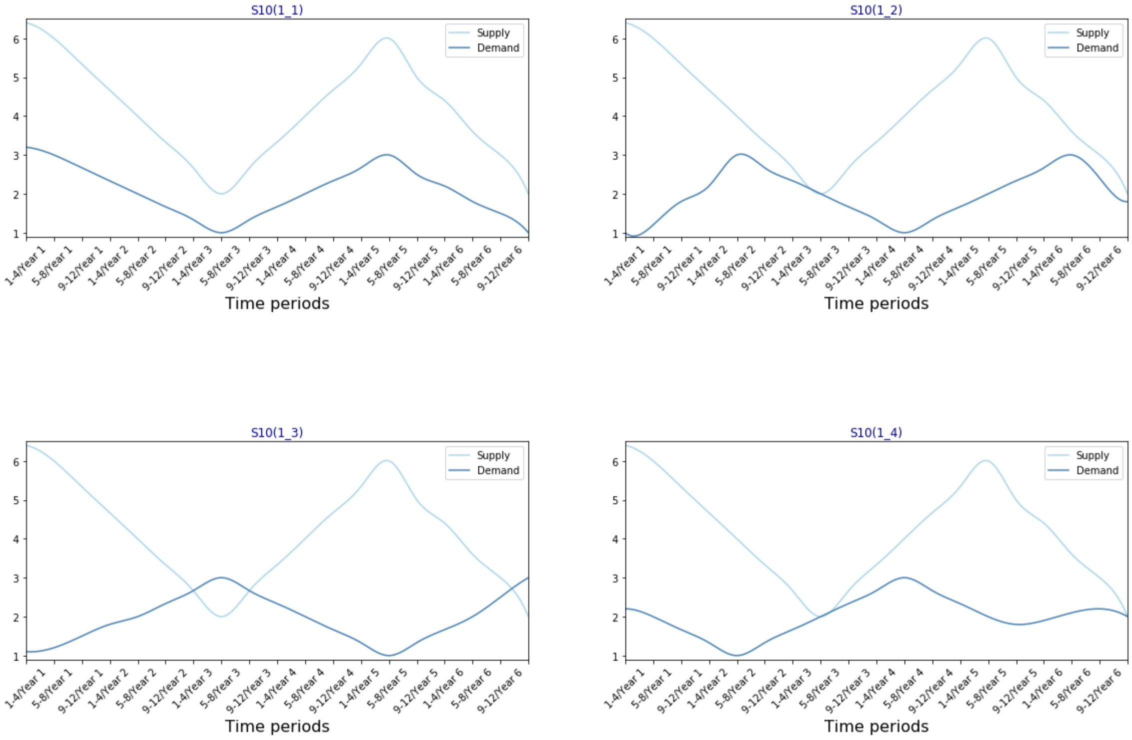
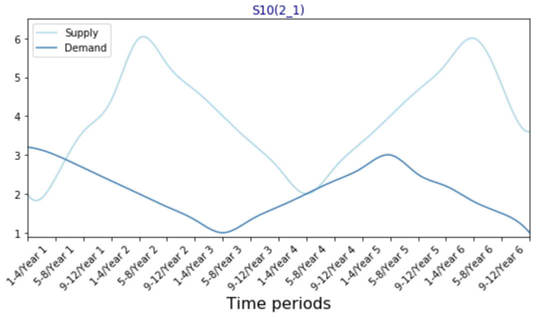


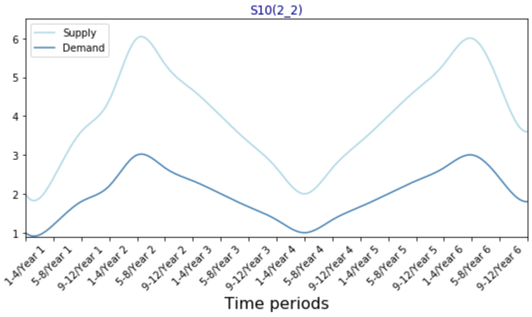
Figure E.32: Sets of instances in scenario S9

Scenario S10

In scenario S10, the sets of instances of supply-demand fluctuation are elaborated in the line plots below (Figure E.40).




S10(2_1)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S10(2_2)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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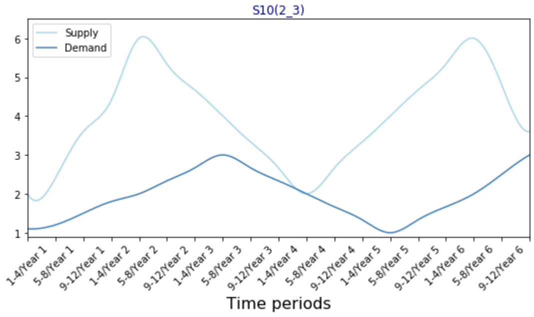
5-8/Year 6
9-12/Year 6
Time periods


S10(2_3)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
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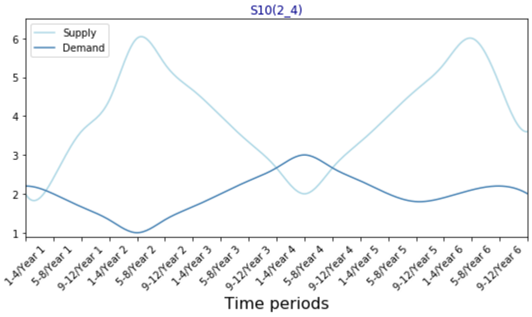
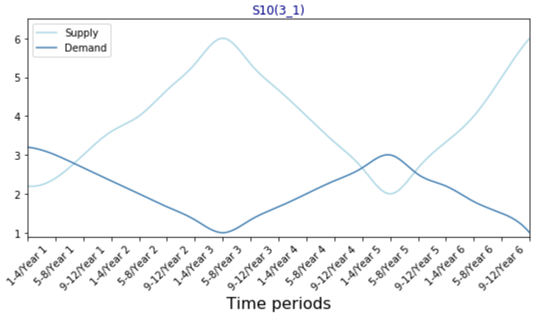
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S10(2_4)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S10(3_1)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
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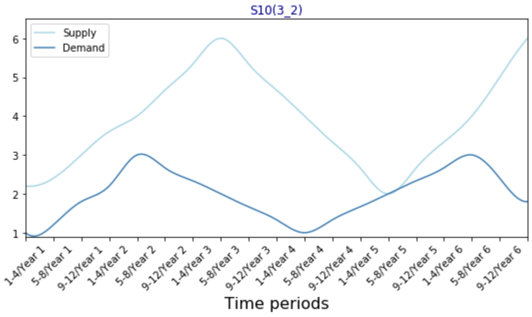
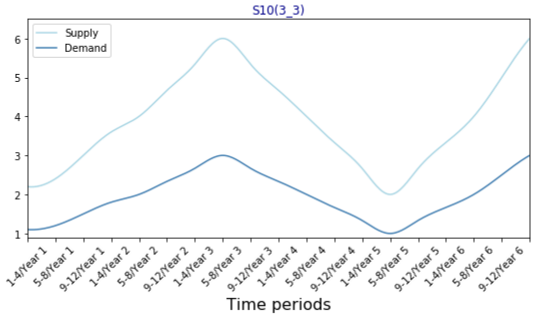
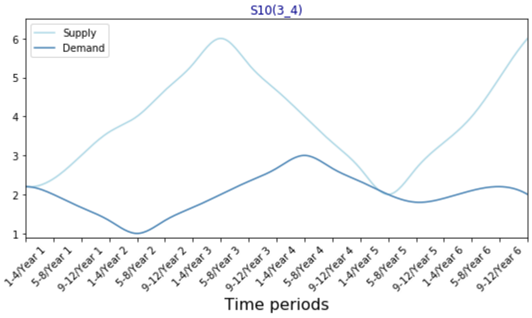
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S10(3_2)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S10(3_3)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S10(3_4)
Supply
Demand
6
5
4
3
2
1
1-4/Year 1
5-8/Year 1
9-12/Year 1
1-4/Year 2
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
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5-8/Year 6
9-12/Year 6
Time periods

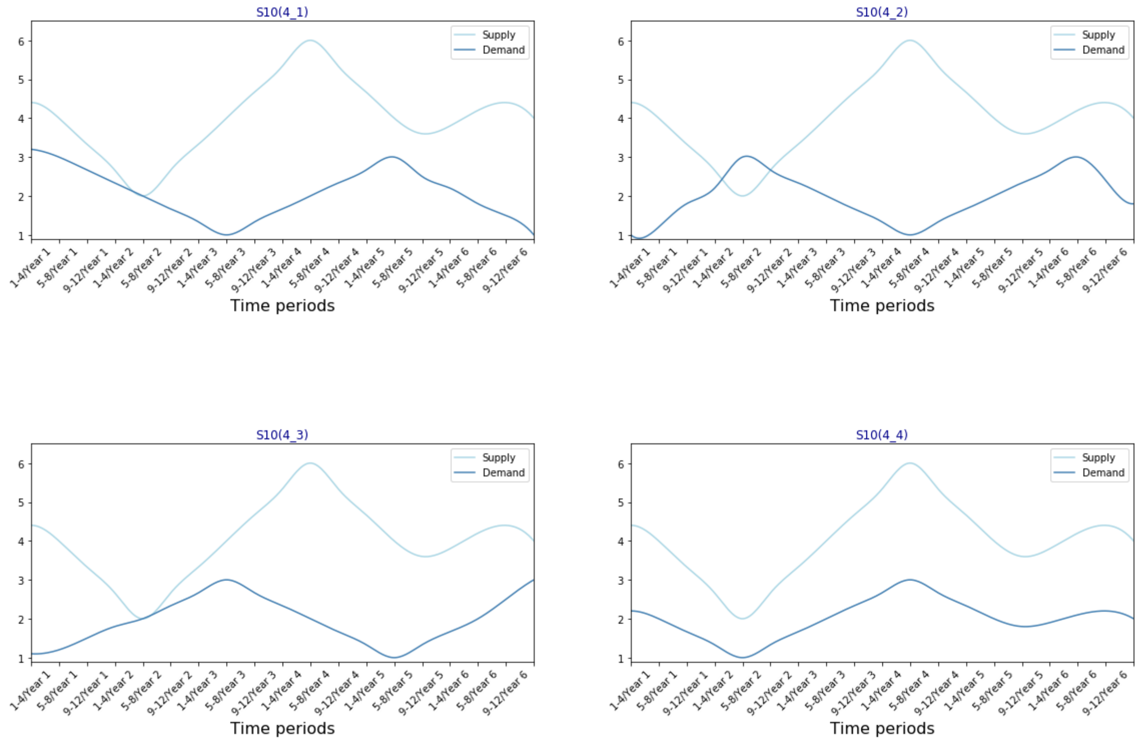
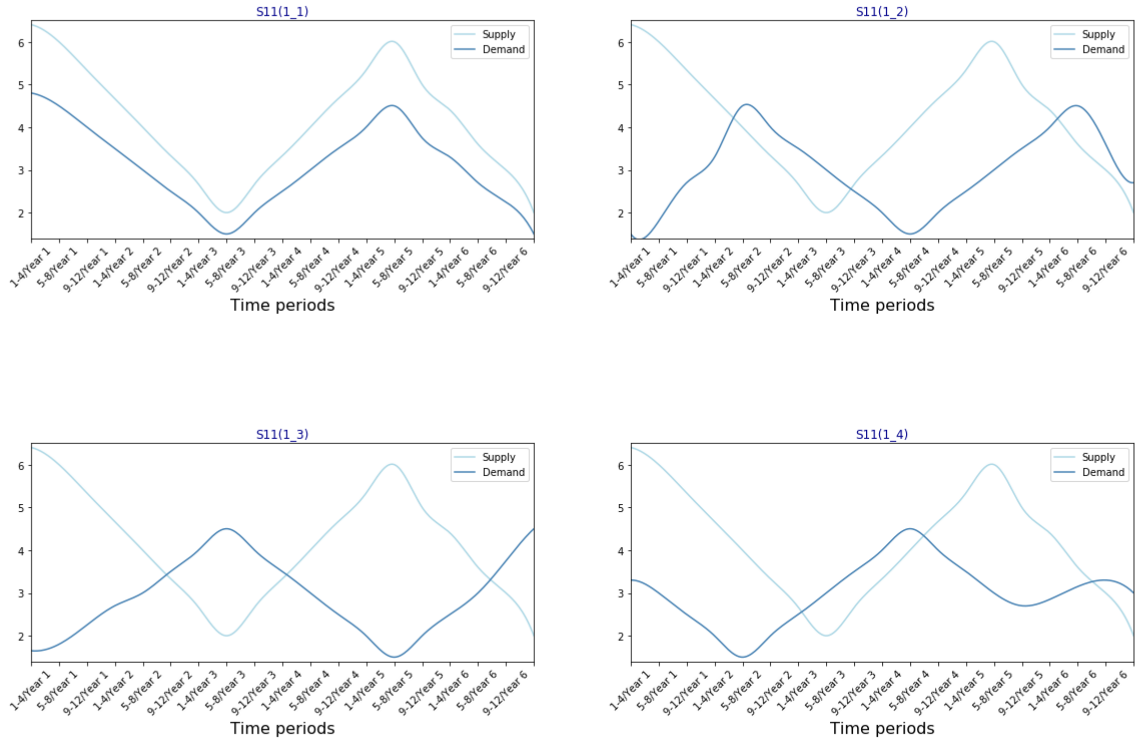
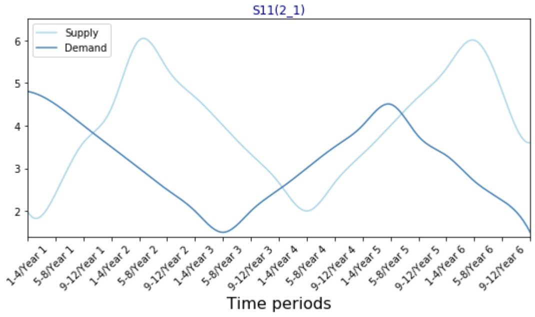


Figure E.40: Sets of instances in scenario S10

Scenario S11

The sets of instances of supply-demand fluctuation in scenario S11 are elaborated in the line plots below (Figure E.48).




S11(2_1)
Supply
Demand
6
5
4
3
2
1-4/Year 1
5-8/Year 1
9-12/Year 1
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5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
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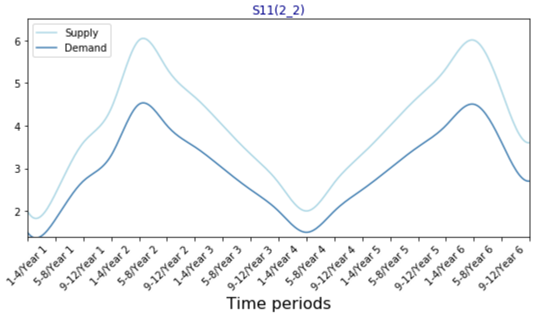
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S11(2_2)
Supply
Demand
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5
4
3
2
1-4/Year 1
5-8/Year 1
9-12/Year 1
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5-8/Year 2
9-12/Year 2
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5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
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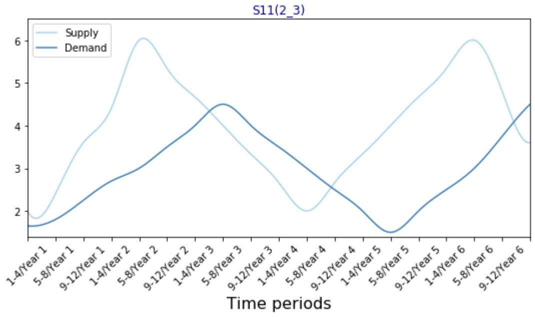
5-8/Year 6
9-12/Year 6
Time periods


S11(2_3)
Supply
Demand
6
5
4
3
2
1-4/Year 1
5-8/Year 1
9-12/Year 1
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5-8/Year 2
9-12/Year 2
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5-8/Year 3
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5-8/Year 4
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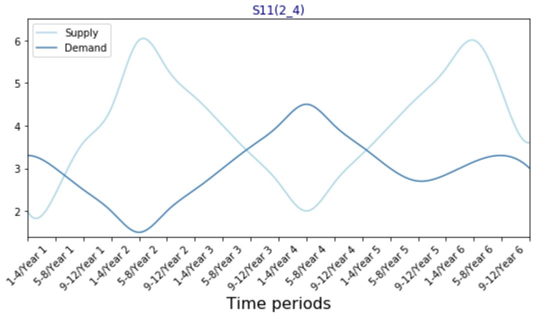
5-8/Year 6
9-12/Year 6
Time periods


S11(2_4)
Supply
Demand
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3
2
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9-12/Year 2
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5-8/Year 3
9-12/Year 3
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5-8/Year 4
9-12/Year 4
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5-8/Year 5
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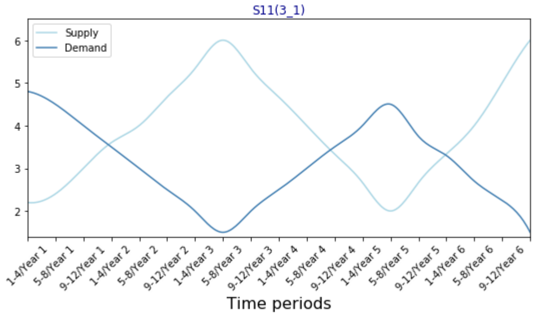
5-8/Year 6
9-12/Year 6
Time periods


S11(3_1)
Supply
Demand
6
5
4
3
2
1-4/Year 1
5-8/Year 1
9-12/Year 1
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5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
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5-8/Year 4
9-12/Year 4
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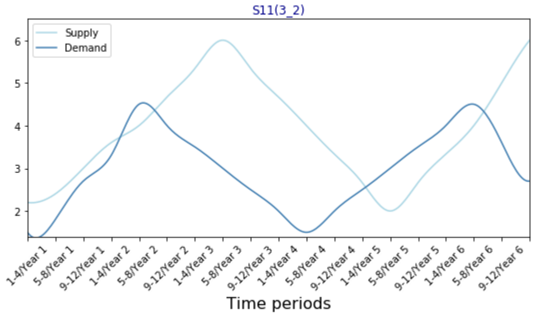
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S11(3_2)
Supply
Demand
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5
4
3
2
1-4/Year 1
5-8/Year 1
9-12/Year 1
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5-8/Year 2
9-12/Year 2
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5-8/Year 3
9-12/Year 3
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5-8/Year 4
9-12/Year 4
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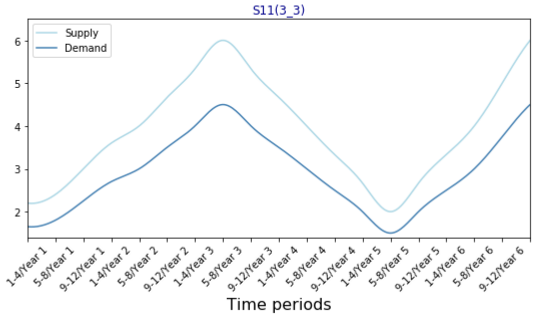
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S11(3_3)
Supply
Demand
6
5
4
3
2
1-4/Year 1
5-8/Year 1
9-12/Year 1
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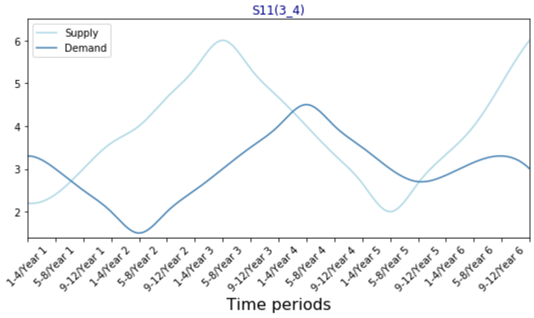
5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
1-4/Year 4
5-8/Year 4
9-12/Year 4
1-4/Year 5
5-8/Year 5
9-12/Year 5
1-4/Year 6
5-8/Year 6
9-12/Year 6
Time periods


S11(3_4)
Supply
Demand
6
5
4
3
2
1-4/Year 1
5-8/Year 1
9-12/Year 1
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5-8/Year 2
9-12/Year 2
1-4/Year 3
5-8/Year 3
9-12/Year 3
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5-8/Year 4
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5-8/Year 6
9-12/Year 6
Time periods

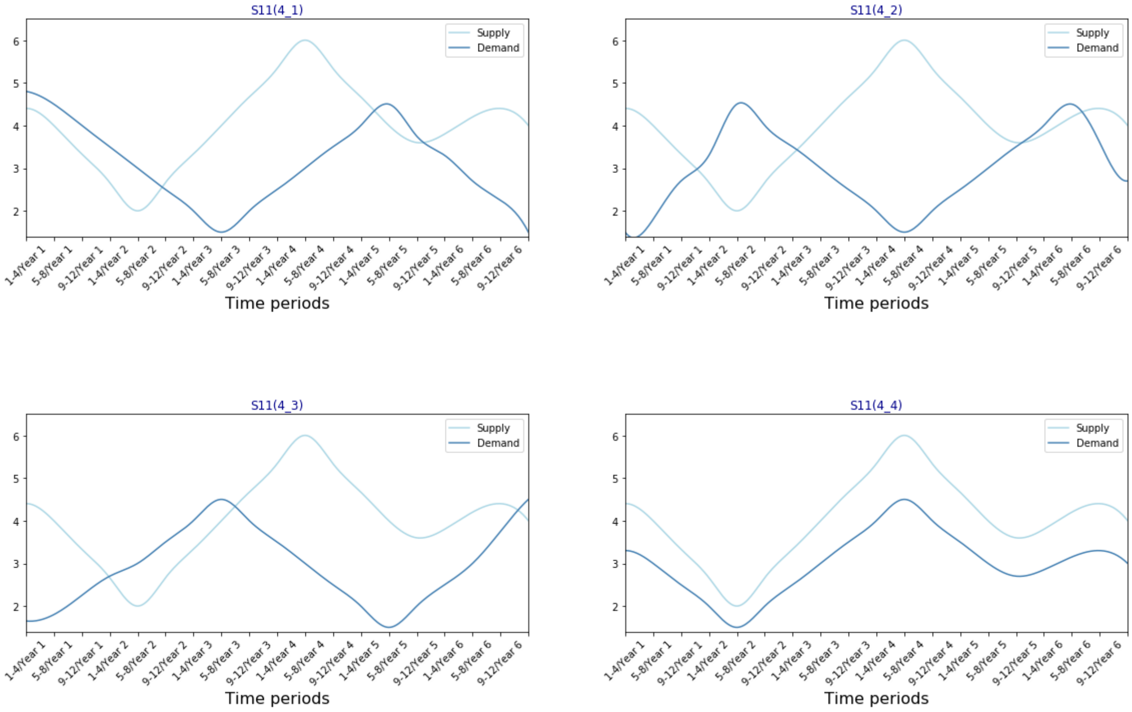

Figure E.48: Sets of instances in scenario S11

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